LESSONS LEARNED

ON THE Skylab

PROGRAM

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FOREWORD

The lessons learned in the Skylab Program are described in five basic documents prepared by and representing the experience of NASA Headquarters, the Lyndon B. Johnson Space Center, the John F. Kennedy Space Center, and the Skylab and Saturn Program Offices at the George C. Marshall Space Flight Center. The documents are intended primarily for use by persons who are familiar with the disciplines covered and who are involved in other programs. Thus, the individual lessons are brief rather than detailed.

Authors of the lessons have been encouraged to be candid. The reader may detect apparent differences in approach in some areas, illustrating that equally effective management action in a particular area frequently can be accomplished by several approaches.

The recommendations and actions described are not necessarily the only or the best approaches, but they reflect Skylab experience that must be tailored to other situations and should be accepted by the reader as one input to the management decisionmaking process. As such, these recommendations, which are based on approaches that were found to be effective in the Skylab Program, should be used to help identify potential problems of future space programs. Many of the lessons are subjective and represent individual opinions and should not be interpreted as official statements of NASA positions or policies.

In addition to the Skylab Lessons Learned documents, Skylab Mission Evaluation Reports are being issued by the previously mentioned NASA agencies to provide detailed evaluation results. The results of the scientific experiments will be disseminated by the Principal Investigators.

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REQUIREMENTS DEFINITION

S.L.L. No.: 1-1

TITLE: MAN AS SCIENTIFIC OBSERVER AND IN-FLIGHT REPAIRMAN

LESSON LEARNED: The Skylab missions demonstrated that man can serve as a scientific observer and in-flight repairman to a substantially greater extent than anticipated before the first Skylab mission. The crews found that the absence of gravity was not a hindrance in performing their planned activities. In many respects, the crews were able to do more than expected.

BACKGROUND: Before the Skylab missions, there were uncertainties as to the ability of astronauts to perform in-flight repairs (either scheduled or unscheduled). The Skylab experience showed that the crews were not hampered by the lack of gravity in any restrictive way. Suitable restraints were needed for all tasks, but existing structure frequently served as suitable restraint.

S.L.L. No.: 1-2

TITLE: IN-ORBIT REPAIR AND MAINTENANCE

LESSON LEARNED: In-orbit repair and maintenance can be performed satisfactorily in zero g. In-flight maintenance guidelines should include the following:

1. Consider extravehicular activity (EVA) as a normal means of repair.

2. Provide proper procedures, tools, and equipment for crew usage.

3. Design equipment to facilitate potential in-flight maintenance.

4. Consider EVA inspection and repair during the design requirements phase of a program.

5. Provide for the effective containment of nuts, bolts, washers, tools, hardware components, etc., by means of tool and/or retainer boxes, bungee cords, etc.

6. Provide for a worksite, repair bench, or equivalent equipped with adequate restraints for tools and equipment.

7. Provide spares for those hardware items most likely to require servicing and/or replacement.

8. Promote the use of standard-size screws, bolts, etc., in the spacecraft design.

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9. Provide a high-fidelity maintenance training simulator.

10. Provide the capability to reservice fluid and gas systems from the interior of the spacecraft. Fluid/gaseous connectors (B-nuts, weld or solder joints) should be located and configured such that they can be inspected by the crew for leaks.

11. Design panels to allow replacement of indicator lights from the front of the panels.

12. Design external protective covers for experiments and other equipment for manual operation by EVA as well as by automatic opening. An EVA manual override may be necessary if automatic opening fails.

13. Single force fasteners should be used to close out all access panels in lieu of slotted or Phillips head screws.

BACKGROUND: The Skylab crew demonstrated conclusively the capability to perform a wide variety of in-orbit maintenance and servicing tasks. Some of the more significant examples were:

1. The Skylab 4 crew reserviced the primary coolant system on the airlock module after the fluid leaked out and the operating pressure had dropped essentially to zero. Reservicing had not been considered until the system started leaking in orbit.

2. Two EVA crewmen freed the OWS solar array wing by cutting a small metal strip, which was holding the solar array beam in a retracted position. The crew used a rope strap to pull on the solar array beam and break the hydraulic damper, which had frozen in the retracted position.

3. A replacement package of six rate gyros was installed by the Skylab 3 crew. The necessary electrical jumper cables were hooked up by EVA.

4. Numerous items of experiment equipment were repaired by the crew after failure in orbit. One case included EVA rewiring of a microwave antenna drive system.

S.L.L. No.: 1-3

TITLE: NEGLIGIBLE EFFECTS OF CREW MOTION DISTURBANCE

LESSON LEARNED: Disturbances caused by crew motion were small enough
to allow solar telescope pointing stability of better than 1 arc second.
Only intentional large motions by the crew were detectable in the solar
telescope images.

BACKGROUND: Crew motion disturbances were essentially undetectable in
the Apollo telescope mount solar telescopes except when the crew
intentionally induced large disturbances. In many cases, the crew
conducted normal experiment or operational activities in other parts
of Skylab without interference to the solar telescope observation.

S.L.L. No.: 1-4

TITLE: VIDEO UPLINK CAPABILITY

LESSON LEARNED: A capability to uplink and to play back video within
the spacecraft should be provided. This would enable the crew to
observe repair procedures worked out on the ground and to see details
of hardware they may have to repair in orbit. Scientific information
such as solar activity drawings or Earth observations data could also
be uplinked.

BACKGROUND: The capability to uplink video was not provided in Skylab;
however, there were numerous times in the mission when it would have
been valuable.

S.L.L. No.: 1-5

TITLE: FOOD SYSTEM DESIGN

LESSON LEARNED: The following three items are recommended in the design
of food systems where long-term space flight is involved.

1.   Response, simplicity, cost, and amount of documentation can be
     optimized if standard menus are planned and provided, so that all
     crewmen are eating the same basic meal at the same time. Indi-
     vidual preferences can be provided in beverage, snack, spices, and
     dessert selection from an onboard pantry.

2. Pantry-type food storage as opposed to meal-sequence food storage: Particularly for long-term flight, it is recommended that a pantry-style food storage system be implemented. In this type system, all identical foods are stored in the same location, and a meal is prepared by selecting the desired foods from the storage area in much the same manner as a home pantry. This stowage arrangement provides flexibility in implementing real-time desires and planning as may be required to support changes to mission duration, time lines, crew health, etc.

3. Operational system as opposed to experiment support: The Skylab food system served two purposes: (1) It was the operational system for supplying the crewmembers nourishment, as well as, (2) being a large element of the MO70, Mineral Balance Medical Experiment series. These types of experiment requirements on the food system involved increased costs and manufacturing complexity and impacted crew preference, and flexibility; at times, these food system requirements increased the overall complexity of mission operations. It is recommended, if feasible, that the operational food system be isolated and controlled separately from the experiment food or formulation that would be used in connection with any nutrition or medical experiments.

BACKGROUND: The Skylab food system provided custom menus for each crewmember. These custom menus were balanced nutritionally and were per the mineral level requirements of the MO70, Mineral Balance, experiment series. The food was then oriented in a meal sequence and loaded in the 11 food lockers by a preestablished orientation list. Before the mission, continuous detail coordination and followup were performed in developing crew menus that met the experiment as well as nutritional and crew preference requirements. Any change in menu before the flight resulted in documentation revision and coordination with the contractors and the NASA offices. Secondly, involved crew procedures and lengthy documentation included cue cards, flight data files, and experiment checklists to document the onboard storage and food use requirements. In essence, the meal-oriented sequence approach provided a single stowage sequence of approximately 8000 items; and, once on board, real-time changes and updates in crew preference, experiment requirements, or menu changes for any reason necessitated excessive food handling and recordkeeping. The pantry arrangement would eliminate much of the paperwork, recordkeeping, and system tracking and would provide maximum flexibility to the crew and to the ground for coping with real-time changes. The pantry-storage approach appears to be most reasonable for long-term missions.

S.L.L. No.: 1-6

TITLE: TRASH COLLECTION AND DISPOSAL

LESSON LEARNED: Trash should be separated into biologically active and inactive material. Daily disposal of active material is necessary, whereas less frequent disposal of inactive material is satisfactory. Stowage of collected trash "external" to the habitable volume of the spacecraft is highly desirable. Food containers make up the bulk of the trash and should be designed to consume minimum volume when expended. A compactor seems like a desirable feature. Backups and contingency plans are necessary.

BACKGROUND: Considerable crew time was spent in Skylab managing the trash situation. Additional temporary collection sites were needed to allow trash to be easily and conveniently stowed during the rush of the workday and collected and disposed of when time allowed. A failure of the trash airlock would have been a significant impact on the habitability of the spacecraft.

S.L.L. No.: 1-7

TITLE: WINDOWS IN SPACECRAFT

LESSON LEARNED: A large, simple window in the Skylab wardroom out of which the crew could observe the Earth and cosmos provided one of the more important means of relaxation. Much of the value of this type window would have been lost if it had not been located in the crew quarters.

BACKGROUND: The Mercury, Gemini, and Apollo missions all demonstrated the value of adequate viewing windows. Although there was appreciable opposition when the wardroom window was proposed for Skylab, this window proved to be invaluable.

S.L.L. No.: 1-8

TITLE: GARMENT REQUIREMENTS

LESSON LEARNED: Two-piece garments (such as pants and shirts, as opposed to coveralls) proved convenient in Skylab for the same reasons as on Earth. Two-piece garments are less sensitive to fit, are more adjustable to clothing requirements, and are more convenient to personal hygiene procedures. Spacecraft interiors are very clean. Clothing gets soiled principally from the wearer's body. More underwear and socks and fewer outer garments should be provided.

Elastic or knitted cuffs to prevent sleeves and pant legs from riding up are not required. They were sometimes an inconvenience. Headgear as a protective device is not required.

Location and design of pockets warrants engineering study and a realization that the types and locations found practical in aircraft flying suits and in streetwear may not be. so practical in space-flight garments. Do not compromise pockets to suit styling of the garment. Garment material must resist abrasion, especially footwear, if it has to interface with "force-fit" type foot restraints.

BACKGROUND: Skylab crews felt that the outer garments could be worn 1 or 2 weeks without needing change, but underwear and socks should be changed daily. They wore out shoe toes rubbing them against the grid flooring.

The crewmen tended to carry everything from nail clippers to maintenance tools in their pockets, and a better pocket design would have been helpful.

S.L.L. No.: 1-9

TITLE: PERSONAL HYGIENE EQUIPMENT

LESSON LEARNED: A wider range of hygiene and grooming equipment and expendables should be provided, probably as a personalized kit for each crewman. The quantity of soap supplied on board Skylab was based on a usage rate of one bar/man/2 weeks plus five bars/month for housekeeping and cleaning tasks, yielding a total of 55 bars. The Skylab 2 crew used only one bar of soap for the entire mission as opposed to the 11 allocated for use. A reevaluation of the quantity of soap to be flown should be made based on the Skylab 3 and Skylab 4 data.

BACKGROUND: Various Skylab crewmen complained that the personal hygiene items did not meet their accustomed standards, and consequently they avoided some items such as the shower soap, toothpaste, shampoo, and razors. The shower soap left some crewmen with a "stinging" sensation, hence they quit using it. The shampoo had a distinctly unpleasant odor, hence was avoided. The toothpaste was not ingestible and the inconvenience of zero-g spitting caused some crewmen to use it sparingly. The safety razors clogged badly with no way to use the one-g "slosh-in-the-water" convention in the zero-g environment.

S.L.L. No.: 1-10

TITLE: INTRAVEHICULAR ACTIVITY AND EXTRAVEHICULAR ACTIVITY RESTRAINTS

LESSON LEARNED: Intravehicular activity (IVA) and extravehicular activity (EVA) foot and body restraints are required to accomplish useful work in zero g in large volume spacecraft. The triangle shoes used for foot restraints with the orbital workshop (OWS) grid floor worked very well at the workstations. Based on Skylab experience, future shoes of this design should be made more durable and should have zippers rather than laces to facilitate donning and removing.

BACKGROUND: Restraints should be uniform throughout the spacecraft and should be attached to the spacecraft and not the crewman. Once engaged, they should require no further conscious consideration until the crewman is ready to disengage. The triangle grid-floor shoes and thigh restraint provided excellent restraints for use in the OWS for IVA work, while a "universal" foot restraint is required for EVA work.

S.L.L. No.: 1-11

TITLE: WRITING AND WORKTABLE FOR IN-ORBIT USE

LESSON LEARNED: Frequent and extensive paperwork activities were required on board Skylab to update checklists, flight plans, etc., and to accomplish routine experimental and operational logging requirements. A suitable writing table or workstation is needed at which this type of activity can be effectively performed.

A table or workstation is also needed to accommodate maintenance on items to be disassembled. It should be equipped with some method of restraining multiple small components during the maintenance task.

BACKGROUND: Writing and managing multiple piece parts in zero g are difficult chores in that environment. Excessive time is consumed doing such routine and simple tasks when proper facilities are not available. The wardroom table did not serve the required purpose because it did not include the type of restraints needed for books and papers. Also, the need to prepare and consume food and to clean up afterwards limited the times when the table was available.

S.L.L. No.: 1-12

TITLE: SPACECRAFT CENTRAL SYSTEM TIMING SOURCE

LESSON LEARNED: The entire spacecraft timing system should have one central timing source. This source should also be used for all payloads or kitted items carried by the spacecraft.

BACKGROUND: The entire onboard and downlink system should be keyed to one central timing source to facilitate data correlation and to minimize ground data processing complexity. The timing system should be capable of being updated at any point in time to reflect the true (actual) time.

All onboard experiments that require time tagging should use the common timing source. The central timing equipment should have sufficient capacity to extend over the entire mission (run) without "rollover."

S.L.L. No.: 1-13

TITLE: INCREASE ONBOARD DATA STORAGE CAPABILITY

LESSON LEARNED: Total onboard tape recording time should be increased to cover at least a normal day's work of experiment activity. This could be implemented with greater online data storage capacity or by using the crew to change tapes in some type of simplified cassette system. Data dump should be accomplished either in parallel with the "workday" or serially during the sleep period.

BACKGROUND: Flight planning constraints existed because of recorder nonavailability when two high data generating experiments were planned back to back. Ground coverage was also a constraint because the experiment data recorders had to be cleared in time for the next run.

S.L.L. No.: 1-14

TITLE: MASS HANDLING AND TRANSFER IN THE SPACECRAFT

LESSON LEARNED: Large masses are easily manageable in zero g. The real problem is in handling multiple small items without a container to "fence them in." The limiting factor in handling large masses is the cross-sectional area, which tends to block the crewman's view of the transfer path and the terminal site if more than approximately 20 by 25 inches. Energy inputs used to initiate transfer must be removed at termination, and care must be taken not to "overdo it."

BACKGROUND: No difficulty was encountered by Skylab crews in moving large masses within the spacecraft. Such items must have provisions for handling, such as handles or integral parts of structure that can be easily grasped. Individual techniques for moving items about the vehicle varied among crewmen, but all adapted well and were quite successful.

S.L.L. No.: 1-15

TITLE: STANDARDIZATION OF HARDWARE

LESSON LEARNED: Crew-use hardware such as fasteners, electrical and plumbing connectors, switches, circuit breakers, and screws, etc., should be standardized as much as possible to facilitate crew operations, reduce crew errors, and reduce crew training requirements. Each common usage also reduces total sparing levels. This approach will simplify design, documentation, sparing, and actual in-orbit usage.

BACKGROUND: With many different types of devices to manipulate, the crew will require more extensive training and is more likely to make errors. These errors could result in lost data, damaged equipment, or in the worst case, crew hazards. Minimizing the number of different types of devices will reduce the chance of error and may result in cost savings by limiting inventory requirements.

S.L.L. No.: 1-16

TITLE: SPECIFICATION REQUIREMENTS FOR BREATHING GASES

LESSON LEARNED: The Skylab 2 gas breathing system presented the need for nitrogen, which was controlled, as required, for breathing purposes. Because mixing of the breathing gas was accomplished in the test chamber or spacecraft system, no analysis of the mixture was possible before its use. Therefore, analysis and control of each gas before system loading were necessary. The NASA Lyndon B. Johnson Space Center (JSC) reviewed the available nitrogen specifications and discovered that even the most stringent specification (MSFC-SPEC-234A) did not adequately control nonhydrocarbon toxic impurities that must be controlled in a breathing gas.

BACKGROUND: The MSFC-SPEC-234A has a stringent purity requirement, but the purity percentage is derived by considering only the controlled impurities. Because the percentage does not include various nonhydrocarbon impurities and cleaning solvents (i.e., Freon 113), the presence of these impurities will not influence the purity rating.

REFERENCE: The JSC has now prepared the requirements necessary for control of nitrogen to be used in breathing gas mixtures. These requirements are reflected in table B of JSC SE-S-0073, Space Shuttle Fluid Procurement and Use Control. These same requirements will be documented in the Apollo/Soyuz nitrogen specification.

S.L.L. No.: 1-17

TITLE: HIGH-FIDELITY TRAINING HARDWARE

LESSON LEARNED: High-fidelity training hardware is mandatory to aid in the development of procedures, to enhance the quality of crew training, and to ensure efficient use of crew time during flight.

BACKGROUND: The extravehicular pressure control unit (PCU) training articles assisted the crew in mastering malfunction procedures as well as in providing them with a better overall systems understanding. Learning time was significantly reduced. The M509 astronaut maneuvering experiment simulator at the Martin Marietta Corporation in Denver was a very effective trainer. No surprises were noted by the crew during flight and they were able to concentrate on the experiment objectives. The S063 ultraviolet horizon airglow experiment training was reported to be inadequate because a simulator could not be devised that would give the crew an idea of what they would actually see. For some experiments, the first few operations during flight were considered to be on-the-job training. The intracommunication system used in the one-g trainers was one of the few systems that had not been designed to duplicate the flight system. Errors in early checklists resulted because procedures could never be adequately verified. The training hardware shortcomings led to reduced effectiveness in crew training.

S.L.L. No.: 1-18

TITLE: MAINTENANCE AND REPAIR DEPOT FOR EXPERIMENT HARDWARE

LESSON LEARNED: Provide a depot repair, maintenance, and modification capability for delivered experiment hardware. Schedule and manpower expenditures were minimized because of the quick turnaround capability afforded by the depot concept of operation and the physical location of the depot in relation to the receiving and shipping docks. The ability to repair items in the depot or to go directly to the proper specialty manufacturing area within the company greatly enhanced the time it took to achieve needed repairs. The small team of people used to run the depot were all "graduates" of the qualification-acceptance test phases (engineering, test, and quality). This fact made the decision process more accurate and timely. Subsequent repairs and tests

were accomplished more efficiently because of the experience of the personnel involved. The depot provided a suitable location for the mission support testing to assist in the investigation of in-orbit anomalies during the Skylab missions.

BACKGROUND: The Skylab depot was a dedicated enclosed area located within the inventory building at the Martin Marietta Corporation Denver plant. It was equipped with an office area, receiving/inspection room, storeroom, and a clean room where all repair and test operations were done. It was established to support NASA Lyndon B. Johnson Space Center experiment repairs and modifications.

REFERENCE: Skylab Program - Postdelivery Operations Plan, JSC-03137.

S.L.L. No.: 1-19

TITLE: BENCH TESTING OF COMPLEX ELECTRONIC EXPERIMENT PACKAGES

LESSON LEARNED: The following recommendations apply to complex electronic experiment packages:

1. Plan a bench test program on a system basis by using development units and simulators initially, followed by flight units to provide system compatibility as early as possible.

2. Plan to update the development units and simulators on a periodic basis so that these units can continue to be used in the overall test program.

3. Provide for an off-module bench test capability using development, qualification, and/or flight backup hardware throughout the entire test program to provide a means to troubleshoot hardware problems with a minimum cost and schedule impact to the flight spacecraft.

4. Consider a mobile bench hardware configuration to support special sensor calibration, testing for end-to-end checkout like the S192 imagery tests, S191 lunar calibration tests, or S192 low-frequency noise vacuum test program.

BACKGROUND: The Earth resources experiment package (EREP) provided for a bench test using development hardware and interface functional test units before installation and checkout of the flight hardware in the multiple docking adapter (MDA). These tests were for the purpose of proving electrical interface and operational compatibility at the earliest opportunity in the Skylab Program.

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Off-module testing of the EREP experiments and hardware identified many systems and individual experiment problems without a day-for-day impact on the MDA flight hardware flow. Most of the problems encountered were in the individual experiments rather than in the interface with the MDA. The bench test setup was helpful in resolving anomalies discovered in flight.

S.L.L. No.: 1-20

TITLE: SPECIAL PROCEDURES FOR HANDLING MAGNETIC TAPE

LESSON LEARNED: To prepare and protect magnetic tape for maximum accuracy of high-density digital data storage, the following special procedures were found necessary and adequate:

1. Magnetic tape was screened by using the same high bit-packing density and track density as the flight data and checked for bit error rate before acceptance.

2. Flight-screened tapes were specially wound by using a programed winding technique that varied the tape tension to be lower at the beginning and end of the winding process to provide an inverted cup-shaped general tape tension profile. This winding process enabled the wound tape reels to withstand a relatively severe launch vibration and shock profile over a temperature from 50° to 110° F. Tape reels that were not programed wound exhibited block shifts and other tape damage that reduced the accuracy of the data in the areas affected.

BACKGROUND: The physical and chemical changes experienced by magnetic tape resulting from exposure to environment extremes are not well known. Normally, this type information is considered as proprietary by magnetic tape manufacturers. The concern from a data acquisition/recovery standpoint is the bit error rate impact resulting from actual tape damage or degradation due to the chemical and physical changes. Results of many magnetic tape-winding tension profile evaluations show that the tension-winding programs developed for Skylab substantially reduced the susceptibility of the tape to handling damage. Skylab experience showed that one of the primary limitations on recording system bit error rate is the quality of the magnetic tape. To determine the magnetic tape bit error limitations, each flight/ground test tape was bit error screened on each of 28 tracks throughout the full tape length to a conservative bit error specification.

REFERENCES: JSC-03143, Development Test Report for EREP Tape Recorder; JSC-05352, Test Report for EREP Magnetic Tape Evaluation Test Program.

S.L.L. No.: 1-21

TITLE: DETERMINATION OF EQUIPMENT QUANTITIES

LESSON LEARNED: Individual hardware suppliers should not independently establish hardware quantities required for program activities. The program organization must establish a consistent approach in determining quantities of equipment required to support a program. A combination events chart and requirements checklist was a useful tool for quantity determination.

BACKGROUND: On Skylab, technical monitors and suppliers did not have sufficient information to determine accurate quantity data such as how many carbon monoxide monitors, television cameras, or clothing modules were to be required to support all ground and flight activity. The project office devised a combination events chart and requirements checklist that assured that enough items would be available and minimized production of unnecessary items. The key factors affecting quantity are breadboard, mockup, prototype, qualification, production for flight, flight backup, trainers, and spare parts. Timing is also important in sequencing usage to reduce total quantities required.

S.L.L. No.: 1-22

TITLE: SHORTEN FLIGHT DATA RETRIEVAL RESPONSE TIME

LESSON LEARNED: Flight data retrieval should be better automated and should be available within a shorter response time.

BACKGROUND: On Skylab, too many man-hours were expended for flight data retrieval. Because science data must be retrieved by someone familiar with the data to ensure proper downstream data handling, the data retriever must be well trained in the experiment and must have a thorough understanding of the ground and onboard data system.

S.L.L. No.: 1-23

TITLE: CRITICALITY CATEGORIES AND HAZARD CATEGORIES

LESSON LEARNED: Criticality categories for single failure points and hazard categories should be uniform for all contractors and all hardware.

BACKGROUND: Differences in definitions and application of criticality categories and hazard categories caused confusion and created problems in preparing hazard analyses and single-failure point summaries.

REFERENCE: OMSF SPD #1A for hazard categories.

S.L.L. No.: 1-24

TITLE: TECHNICAL SPECIFICATIONS FOR EXPERIMENTS OR GOVERNMENT FURNISHED EQUIPMENT

LESSON LEARNED: The minimum number of key operating parameters should be specified in technical specifications. If a specification is written with all performance parameters identified with tight tolerances, the danger is that the learning process associated with a development of a new concept will involve many potential violations of the contractual specification. It may be that the new concept or approach deletes the need for many of the tolerances or even some of the specified parameters. Where new technology is to be permitted in a proposal, the tendency should be to write the performance specification in terms of only the key parameters. Detailed component operating characteristics and tolerances should be established later through NASA-approved contractor specifications.

BACKGROUND: When the astronaut life support assembly end-item specification was being written, it was realized that there were two methods of providing pressure control and flow rate to the extravehicular mobility unit. One method had been used during the Gemini and Apollo Programs. Another method involved upstream regulation and downstream flow control. To afford bidders the opportunity to present the widest spectrum of potential design, the end-item specification, written at the NASA Lyndon B. Johnson Space Center, allowed for both approaches. (However, there was an additional ground rule that only proven hardware or designs could be used.) Although the generation of the specification was done with the best available technical input, the tolerances were later found to be more stringent than necessary.

S.L.L. No.: 1-25

TITLE: OPERATIONS DOCUMENTATION REDUNDANCY

LESSON LEARNED: Mission documentation should be consolidated and should have little or no overlap. Conflicts develop quite frequently when two or more control documents cover the same items.

BACKGROUND: Both Skylab Mission Rules and the Mission Requirements Documents (MRD) included instructions relative to experiment constraints. Because the MRD had wider program authority, it should have been the control document. The constraints should have been written in the MRD in a format that was compatible with the Mission Rules. During Skylab, MRD updates were shown on Flight Operations Management Room forms and had visibility long before Mission Rules were considered.

The operations handbooks and the crew checklists also overlapped. These documents should be combined and should be written by the same individuals.

The Operations Data Book items should be combined with the systems handbooks so that hardware performance and operations are all contained under one cover.

S.L.L. No.: 1-26

TITLE: ACCURACY REQUIREMENTS FOR EPHEMERIS DATA

LESSON LEARNED: In the development of requirements for various data-base ephemerides in future planning applications, accuracy requirements for both real-time and postmission analysis should be an integral part of the documentation.

BACKGROUND: Planning systems, such as the mission operations planning system (MOPS), have many diverse users. Each user has certain minimum accuracy requirements for the ephemeris he is accessing. For Skylab, these requirements were never documented, which made the task of maintaining the trajectory very subjective. Because maintenance of these various trajectories is simply a service function, the absence of firm accuracy requirements makes it impossible to establish a definite priority on these updates. Certain long-range planning functions required essentially no accuracy while detailed real-time work like Earth resources experiment planning necessitated extremely accurate trajectory data. While MOPS updates in Skylab were more than adequate to meet all user requirements, more widely used systems in the future must be maintained by using positive standards with which to justify updates.

S.L.L. No.: 1-27

TITLE: PRINCIPAL INVESTIGATOR BATCH-TYPE SOFTWARE SUPPORT

LESSON LEARNED: A software approach that allows quick software development by the Principal Investigator (PI) should be provided. The software support system should be built with the following considerations:

1. Detailed software documentation should not be required of the PI. He or one of his programing representatives should be available any time his software is run operationally.

2. Data input routines should be standardized and provided by NASA with appropriate controls to protect the input data.

3. Data output devices and display packages should be standardized as much as possible.

4. Investigators should be provided with a software manual, which describes the standard NASA systems, inputs, outputs, and general purpose software units (i.e., statistics routines) that are available to the user on request.

BACKGROUND: The lead time requirement levied on Skylab PI's for software development was not reasonable from a scientific point of view. The software implementors wanted detailed software requirements developed at least 2 years before flight. Many PI's did not yet have operational hardware at the time and experiment protocols were still undefined. The type of system proposed would be similar to normal batch-type operations so that production activity could continue in a normal manner from mission operations to job shop.

S.L.L. No.: 1-28

TITLE: TRANSCRIPT LIBRARIES FOR RECORDED VOICE AND AIR-TO-GROUND VOICE DATA

LESSON LEARNED: The transcript library function was very useful and brought order out of chaos. This type of capability should be used and expanded in future missions to include documentation filing.

BACKGROUND: Transcripts are necessary. Voice tapes cannot be readily reviewed by all personnel at one time. The cataloging task performed by the transcript library was very helpful.

TITLE: DATA PROCESSING RESPONSE TIMES FOR MISSION CONTROL CENTER

LESSON LEARNED: An integral part of building a software system for the Mission Control Center (MCC) must be to ensure that adequate response time is provided for all computations. In some mission phases, the strictest requirements on response time may dictate processing priorities inconsistent with mission operations in other phases of flight. Further, all software requirements should indicate specific response times required, when applicable.

BACKGROUND: In Skylab, telemetry processing was given a higher priority than trajectory processing because, generally, telemetry processing was considered more important. In some mission phases, however, time critical trajectory computations were mandatory for crew safety and mission success, and these computations were held out an unacceptable length of time because of telemetry processing. Although a workable arrangement was finally realized by stripping down extraneous processing to a minimum (and several other compromises), a permanent fix was not implemented.

SECTION 2

DESIGN

S.L.L. No.: 2-1

TITLE: CAPABILITY FOR EXTRAVEHICULAR ACTIVITY ACCESS, PATHS, AND HANDHOLDS

LESSON LEARNED: Extravehicular activity (EVA) access should allow the crew to go to any point on the exterior of the spacecraft. Paths should be established and handholds provided such that the crew can traverse to any point on the exterior of the spacecraft. If fixed restraints are not feasible, alternate design concepts should be considered.

BACKGROUND: Skylab EVA paths were limited by the 60-foot length of the EVA umbilicals and, in some cases, by the lack of handholds. Universal EVA foot restraints were designed for use on the later Skylab missions.

S.L.L. No.: 2-2

TITLE: EXTRAVEHICULAR ACTIVITY AND SPACE VEHICLE DESIGN COMPATIBILITY

LESSON LEARNED: Space vehicle design, from mission conception, should accommodate extravehicular activity (EVA) as a planned normal operation; that is:

1. The airlock should not be located in the center of the vehicle between habitable areas.

2. The airlock should be large enough to accommodate two suited crewmen and an assortment of hardware.

3. Electrical and television outlets should be provided external to the vehicle.

4. Adequate restraints, handholds, etc., should be provided inside the airlock.

BACKGROUND: The location of the airlock module precluded access to the orbital workshop (OWS) during Skylab EVA. This situation was not a major problem for Skylab, but it was recognized as a basic design limitation. The equipment needed for EVA had to be moved into the airlock module or multiple docking adapter (MDA) before EVA. As early as 1967, the basic Skylab design with the airlock in the center was recognized as undesirable. However, because of other program constraints, no action was taken to relocate the EVA airlock.

S.L.L. No.: 2-3

TITLE: EXTRAVEHICULAR MOBILITY UNIT/EXTRAVEHICULAR ACTIVITY LIFE-
SUPPORT HARDWARE DESIGN

LESSON LEARNED: Future extravehicular mobility unit (EMU)/extravehicular
activity (EVA) life-support hardware should stress small self-contained
modular rechargeable units as opposed to umbilical designs.

BACKGROUND: Numerous instances of umbilical management problems occurred
during each Skylab EVA, especially those for which the crew had received
minimal or no one-g training. Because of the required handling associated
with an umbilical system (i.e., unstowing, stowing, untangling from
structure and EVA crewman, managing for a transferring crewman, keeping
out of work area, preventing damage to experiments, etc.), a small
amount of overhead must always be added to an umbilical-supported EVA
which, if not a constraint, is at least a nuisance that distracts from
the EVA task. This is in addition to the limited radius of operation
afforded by a fixed-length umbilical system.

S.L.L. No.: 2-4

TITLE: SPACE SUIT AND FABRIC DRYING

LESSON LEARNED: The space suits dried very rapidly in the orbital
workshop (OWS) drying stations, without accumulating objectionable odor
as had been expected. Suit drying and stowage in the cabin atmosphere
was an acceptable procedure. Towels, washcloths, and damp clothes also
dried very rapidly in the low humidity of the OWS. The towel holders
worked well, but all corners of the item being dried had to be
restrained so that the item did not extend into the work areas.

S.L.L. No.: 2-5

TITLE: WASTE MANAGEMENT SYSTEM DESIGN FEATURES

LESSON LEARNED: The airflow system for collecting feces and urine
worked well for Skylab; thus, this concept is recommended for future
spacecraft. For fecal collection, higher airflow than that used on
the Skylab system would be desirable. The seat should be fabricated
of a softer material, and the outside diameter should be widened to
provide a better airflow seal. The lap belt and handholds were abso-
lutely required. The urine collection system should provide for a
volume of at least 4000 ml/man/day. The urine separator should not be
as noisy as the one used on Skylab. The cuff system for collecting

urine was satisfactory as a contingency mode. The urine collector should be refrigerated or stored in a sealed condition to prevent odor buildup. The waste management compartment should be located sufficiently far from the sleep compartment to minimize noise disturbance to sleeping crewmembers. The same blower design was used for the fecal collector, the shower, and the vacuum cleaner on Skylab. This commonality simplified design and maintenance and reduced costs. The in-orbit hand washer that consisted of a water dispenser and cloth squeezer was satisfactory. An enclosed design permitting the crewman to actually wash with the water rather than having to soak up everything in a washcloth would be desirable.

S.L.L. No.: 2-6

TITLE: ONBOARD STOWAGE DESIGN

LESSON LEARNED: Designers of onboard stowage facilities for future spacecraft should consider the following:

1. Individual food stowage items should be located conveniently near the crewman's place in the wardroom.

2. Spacecraft control panel numbers and stowage location numbers were often confusing because they were similar (both used form such as F586). Control panel identification numbers should be created in a format different from that used for stowage location numbers.

3. Standard stowage lockers and locker doors should be used wherever possible. A standard hole pattern for attaching hardware on the door was very useful.

4. To provide two-hand access to the inside of the lockers, locker doors should have sufficient friction in the hinges to hold the doors in the open position.

5. Specialized stowage restraints, cushions, filler material, and separators were found not to be required. Clothing items, towels, and other compressible soft goods were substituted for packing material with substantial cost and weight saving.

6. The capability for rapid assessment of additions, deletions, and changes in equipment stowage should be provided, using mockups, trainers, and simulated lockers.

7. Stowage interface control documents and installation drawings should be required only when there are critical interfaces.

8. Stowage configuration was documented quickly and effectively in photographs.

BACKGROUND: With the Skylab wardroom design, when all three crewman were eating, the crewman seated in front of the pantry had to move out of the way while the other crewmembers unstowed their food from the pantry. Stowage of each crewman's food directly behind his position at the wardroom table would have alleviated this problem.

Weight and volume were very much in demand in the Skylab 2, 3, and 4 command modules. Substantial stowed equipment was added to the spacecraft when towels and clothing were used for padding instead of customized cushions and restraint straps. Frequent last-minute changes to the stowage configuration dictated a quick response method for documenting the configuration. Photography served this purpose well.

S.L.L. No.: 2-7

TITLE: USE OF CLOSED CELL FOAM MATERIAL FOR LAUNCH STOWAGE RESTRAINTS

LESSON LEARNED: Closed cell material used for stowage restraints should have an allowable tolerance to account for changes in volume at different pressures.

BACKGROUND: A problem was identified with mosites foam swelling and shrinking at certain pressures. Because of this phenomenon, the various configurations for which the mosite was initially used resulted in the following conditions:

1. At 26 psia, sample specimens showed a 23-percent decrease in thickness. If this material were fitted for use as a cushioning spacer for hardware under standard atmospheric conditions, its effectiveness at higher pressure levels would be seriously impaired.

2. At 5 psia, representative specimens showed a 5-percent increase in thickness. Thus, standard atmospheric designs for cushioning hardware would "lipover," making it more difficult to remove the supported object.

REFERENCE: MMC letter 72Y-74,246, 21 Aug., 1972. Subject: Contract NAS 8-24000, MSC-145, Plan for Resolution of the Mosites Foam Swelling/ Shrinking Problem.

S.L.L. No.: 2-8

TITLE: SPACECRAFT ELECTRICAL POWER SYSTEMS DESIGN

LESSON LEARNED: Electrical power sharing of the orbital workshop and
the Apollo telescope mount proved to be invaluable. Future spacecraft
electrical systems should have the capability of switching the available
power from major modules or sources to where they will do the most good.
Use of common connectors and good access redundancy on power systems
are required.

BACKGOUND: The loss of one of the Skylab solar arrays at launch led to
critical electrical power situations that were solved by sharing the
available electrical power among several spacecraft modules. Subsequent
failures in orbit were handled by adjustments in shared power
distribution.

S.L.L. No.: 2-9

TITLE: DESIGNING TO DETECT TRANSIENTS IN SPACECRAFT POWER SYSTEMS

LESSON LEARNED: Electrical power systems should be instrumented to
provide sample rates high enough to detect transients. When selecting
telemetry measurement points and the rate of transmission, consideration
should be given to how the data will be used to analyze a problem.

BACKGOUND: When S055 hardware experienced a power transient, the main
bus current could only be analyzed at 1 sample/second in near real time.
Experiment bus parameters were not included on the auxiliary storage
and playback recorder.

S.L.L. No.: 2-10

TITLE: SPACECRAFT TELEMETRY DESIGN

LESSON LEARNED: Systems data should be taken from points that provide
a direct indication of the function being monitored.

BACKGROUND: The aperture door telemetry parameters on the Apollo tele-
scope mount were derived from relays that changed state as a function
of the command but not as the door opened or closed. Consequently,
the telemetry did not provide a credible indication of door position.

TITLE: SPACECRAFT SYSTEM FAILURE DETECTION SEQUENCE CONTROL

LESSON LEARNED: Where spacecraft system redundancy management schemes cycle automatically from multiple to single sensor configurations, the capability must exist to enable/inhibit the redundancy management function at discrete points in the failure isolation sequence as well as to enable/inhibit the function in general.

BACKGROUND: Skylab rate gyro redundancy management monitored three rate gyros for failure indications. If redundancy management detected a faulty gyro in control, that gyro was disregarded and the system was reconfigured for control of the two remaining gyros. If an additional failure was detected, single gyro control was selected. A "reasonableness" test was incorporated to determine the operating status of the remaining gyro, and failure to pass this test resulted in no attitude reference about the affected axis. The redundancy management scheme then automatically configured to "attitude hold" in the two remaining axes.

This scheme, like most redundancy management schemes, was subject to error, especially when the system was subjected to large disturbance torques. For this reason, rate gyro redundancy management was inhibited on many occasions when a specific attitude control mode was required. This action was taken to preclude the system from automatically changing modes to "attitude hold." If a selective enable/inhibit function had existed, the single gyro failure isolation could have been bypassed while still retaining the automatic redundancy management for the three- and two-gyro configurations.

TITLE: SPACECRAFT SYSTEM HEATER MANAGEMENT AND CONTROL

LESSON LEARNED: If heaters are provided to maintain a spacecraft system in a desired temperature range, a backup manual control capability should be provided. To facilitate this manual control, the heater should be undersized. (That is, it should have a much longer "on" cycle than "off.") The failure mode for the automatic heater control should be fail safe (fail off).

BACKGROUND: Skylab rate gyros had many problems associated with failed "on" heaters. If heater enable/inhibit functions had been provided, it would have been possible to manually maintain the temperature in the desired range and keep the system operational.

On the control moment gyro system, the ground heater management function had to be used extensively. However, the task was greatly complicated by the short heater "on" times required. Special care was required to preclude the temperature exceeding the automatic shutoff upper limit or manual control would have been lost for at least one automatic cycle. If the heaters had been undersized, the "on" cycle would have been longer and operational management less difficult.

S.L.L. No.: 2-13

TITLE: BACKUP SYSTEMS

LESSON LEARNED: Where primary systems are untried or overly complex, the backup system should be different and simpler in design to provide "true" redundancy.

BACKGROUND: Skylab came very close to losing all rate gyros in a single axis because of generic design problems with the gyros. If there had been some kind of simplified backup system to allow degraded performance, this failure could have been tolerated without the risk of mission termination.

S.L.L. No.: 2-14

TITLE: SPACECRAFT ATTITUDE MANEUVER STORAGE REQUIREMENTS

LESSON LEARNED: The onboard computer should have the capability for storing a series of attitude maneuvers and their times of execution.

BACKGROUND: The capability to load a series of attitude maneuvers would relieve the crewman of the time-critical task of loading maneuvers individually and would allow concentration on the preparation and execution of other activities.

S.L.L. No.: 2-15

TITLE: PRIVATE AIR-TO-GROUND COMMUNICATIONS

LESSON LEARNED: Private air-to-ground (A/G) communications should not require reconfiguration of the spacecraft and ground operational A/G system but should be included as a mode of operation designed into the spacecraft and ground systems. Additionally, scrambling should be considered to ensure privacy.

BACKGROUND: The Skylab private A/G capability required reconfiguration of both the spacecraft and the ground systems. On several occasions, this resulted in out-of-configuration problems and the loss of scheduled communications, private conversations to be recorded, and/or the release of private A/G voice at ground facilities. In essence, if private A/G communication is to be implemented, it should not be dependent on multiple work-around procedures that are subject to operator errors.

S.L.L. No.: 2-16

TITLE: CAPABILITY TO CHANGE ONBOARD CRITICAL LIMITS

LESSON LEARNED: The capability to change critical limits for the caution and warning system should be provided to compensate for unanticipated variations in the orbital environment.

BACKGROUND: During Skylab, it was necessary to inhibit certain caution and warning inputs because of temperature and pressure changes associated with Beta angle deviations. This bypassed all limit sensing of the inhibited parameters until they returned to the premission limits.

S.L.L. No.: 2-17

TITLE: MANUAL ENTRY DEVICES FOR SPACECRAFT COMPUTER

LESSON LEARNED: Manual entry devices for the spacecraft computer should permit the crewman to view each digit as it is entered rather than showing only the completed entry. Editing capability for the inputs is desirable.

BACKGROUND: Editing capability would facilitate making accurate entries into the computer.

S.L.L. No.: 2-18

TITLE: ATTITUDE SENSOR UPDATES TO SPACECRAFT COMPUTER

LESSON LEARNED: The capability should be provided to inhibit attitude sensors from updating the computer when either hardware malfunctions or special procedures cause such updates to be undesirable.

BACKGROUND: On Skylab, updates to the computer by the star tracker were sometimes incorrect. Attitude updates by the acquisition Sun sensors were not always desirable during certain maneuvers.

<div align="right">S.L.L. No.: 2-19</div>

TITLE: LOADING MEMORY OF SPACECRAFT BACKUP COMPUTER

LESSON LEARNED: The capability should be provided to update and monitor the backup computer without bringing it on line for control.

BACKGROUND: Without the capability to update the backup spacecraft computers, they cannot be kept in an updated configuration with the latest flight program. On Skylab, a switchover to the backup Apollo telescope mount computer required immediate program updates to bring it up to the flight configuration. The capability to monitor the off-line computer without bringing it on line would permit knowing the condition of the backup capability at all times.

<div align="right">S.L.L. No.: 2-20</div>

TITLE: VISUAL ATTITUDE REFERENCE

LESSON LEARNED: A visual attitude reference independent of the control system displays should be provided in manned spacecraft.

BACKGROUND: The loss of the star tracker on Skylab resulted in loss of the Z-axis attitude determination capability. No "out the window" clues were provided to aid the crew in making this determination. As a result, the crew could not position the Skylab in the correct Z-axis attitude without instructions from the ground.

<div align="right">S.L.L. No.: 2-21</div>

TITLE: ONBOARD SYSTEMS DATA RECORDING

LESSON LEARNED: Onboard data recording systems should include sufficient data to adequately determine the cause of out-of-coverage failures.

BACKGROUND: Skylab data recorders contained only a bare minimum of systems data. The sample rate of these parameters that were recorded was too slow for detailed troubleshooting (i.e., 1 sample/4 sec for computer data). The flight controllers were often handicapped by lack of information on failures that occurred while the vehicle was out of contact with ground stations.

S.L.L. No.: 2-22

TITLE: SOFTWARE UPDATE CAPABILITY

LESSON LEARNED: The capability should exist to incorporate software modifications into all spacecraft onboard computers simultaneously as well as selectively to a specified computer or set of computers.

BACKGROUND: On Skylab, software patches could only be made to the spacecraft online computer. If a switchover occurred to the backup computer, it was necessary to make multiple software patches to bring the "new" computer up to date.

S.L.L. No.: 2-23

TITLE: RECOGNITION OF GROUND/CREW INTERFACES IN SYSTEMS DESIGN

LESSON LEARNED: Ensure that spacecraft systems design is such that routine ground activities do not force interruption of the crew activities.

BACKGROUND: Even with voice warning calls from the ground, routine dumping of the voice recorder caused frequent interruption activities and sometimes resulted in loss of data.

S.L.L. No.: 2-24

TITLE: OVERRIDE OVER AUTOMATIC VALVES

LESSON LEARNED: Consideration should be given to providing either mechanical or electrical override capability for all valves that operate automatically. The capability to place a valve in a desired position or to manipulate a stuck valve should be provided.

BACKGROUND: A double failure was experienced in the airlock module coolant loops and refrigeration systems. The temperature control valve B in both the primary and secondary airlock module coolant loops stuck and the radiator bypass control valve stuck in the primary and secondary refrigeration systems. In both cases, had manual control over these valves been provided, the crew could have adjusted the valves to an optimum operating range, thus regaining full systems capability.

S.L.L. No.: 2-25

TITLE: LOCATING TEMPERATURE TRANSDUCERS ON FLUID LINES

LESSON LEARNED: Local hot or cold spots can occur within fluid lines in a spacecraft in orbit when there is no fluid mixing or convection to supplement the normal conduction mode of heat transfer. This condition should be considered in choosing the locations of control or monitoring transducers.

BACKGROUND: During the Skylab 4 mission, the monitoring measurements on the command and service module (CSM) service propulsion system (SPS) oxidizer line indicated erroneous local temperatures rather than the mixed-mean temperature or the maximum temperature of the oxidizer being heated by a strip heater located diametrically opposite the temperature transducers on the oxidizer feedline.

S.L.L. No.: 2-26

TITLE: SINGLE-MEMORY READOUTS FROM SPACECRAFT COMPUTER

LESSON LEARNED: Telemetered single-memory readouts selectable from the ground are useful to the ground in determining the onboard computer load at a given address when large memory dumps are impractical.

BACKGROUND: Such readouts would be helpful in solving unforeseen problems, provided the command capability exists to address any location of interest.

S.L.L. No.: 2-27

TITLE: EXPERIMENT/SPACECRAFT DESIGN COMPATIBILITY

LESSON LEARNED: The performance of a given experiment should be as independent of the spacecraft as possible. The day-to-day activities in the spacecraft should not be severely restricted because of various operation constraints of the experiment.

BACKGROUND: Because of the unique requirements and operating constraints of some of the corollary experiments, other on-going activities in the Skylab workshop had to be curtailed or altered. Accordingly, flight planning for those experiments was often limited to minimum levels; the crew's efficiency was reduced while other experiments were perturbed.

S.L.L. No.: 2-28

TITLE: UNATTENDED OPERATION OF EXPERIMENT HARDWARE

LESSON LEARNED: In designing experiment hardware, consideration should be given to unattended operation requiring only an initiation command. If the experiment can be operated unattended, the crewman is freed for other tasks, additional time becomes available for experiment operations, and flight planning is simplified. Commands to control the experiment could be initiated by either the ground, an onboard computer, or by automatic sequence within the experiment itself.

BACKGROUND: As a general rule, if the performance of a given experiment required the full-time support and attention of the crewman to satisfy its data-gathering requirements, it resulted in inefficient use of crew time, undesirable flight-planning constraints, loss of experiment operation during sleep periods, etc.

S.L.L. No.: 2-29

TITLE: TIME CORRELATION OF VIDEO RECORDER DATA

LESSON LEARNED: Spacecraft video recorders should have the capability to "time tag" data that are dependent on the time at which they were recorded.

BACKGROUND: It was extremely difficult to determine when many Apollo telescope mount sequences were recorded on the video tape recorder. The only sequence indicator available was the time the tape was dumped to the Spaceflight Tracking and Data Network. Lack of timing information for the events recorded decreased the value of the video as scientific and planning data.

S.L.L. No.: 2-30

TITLE: FOOD RECONSTITUTION SYSTEM

LESSON LEARNED: Additional design effort is needed in the food rehydration area to further reduce the problem of entrapped gas.

BACKGROUND: The metering dispensers for hot and cold reconstitution water for food items contained entrapped or dissolved gas. This entrapped gas made reconstitution difficult. Although this problem was recognized during ground-based testing and observed in previous

flights, it still occurred. The gas, in addition to making reconstitution difficult, inflated the food package to a volume larger than that of the nominal design. As a result, heating of the food in the food tray was sometimes inadequate.

S.L.L. No.: 2-31

TITLE: FOOD SYSTEM STORAGE LOCKERS

LESSON LEARNED: Realistic dimension tolerances should be standardized on large volume food system storage lockers to minimize interface problems, shimming, and test requirements.

BACKGROUND: The storage volume for the food system in the spacecraft was defined early in the program cycle, allowing the food lockers to be built with poor tolerance control, which resulted in 11 different sizes for the 11 different lockers. Maximum tolerance buildup in each direction could exceed 0.5 inch. The loaded food restraint assemblies were to fit all lockers. These restraint assemblies were quite massive and, once in orbit, were required to be removed by the crew. The use of shims was unsuitable because the odd shapes (wedges) of the lockers would not allow shims and/or the inserts to be removed after inserting the food restraint assemblies in the lockers. As a result, internal damping techniques inside the canisters, cans, and restraint assembly were used to provide the vibration isolation required to protect the food. Extra development and testing were required to qualify the system.

S.L.L. No.: 2-32

TITLE: GROUND-TO-AIR COMMUNICATION VERIFICATION

LESSON LEARNED: A system for verifying onboard receipt of teleprinter messages is needed, as well as a scheme for managing the large quantities of onboard data received by teleprinter.

BACKGROUND: From time to time, a Skylab crewman would omit a task or perform one improperly because he had not received a message or had received one that was in error. Being greeted with a 10-foot-long series of messages from the teleprinter each morning and having to distribute as well as keep track of them through the day (or for several days) was a continuing problem.

Missions with open-ended workdays of great operational and experimental flexibility must necessarily interchange extensive amounts of information between the ground and the spacecraft. With limited station coverage for voice communications, the teleprinter in Skylab was mandatory.

S.L.L. No.: 2-33

TITLE: INTRAVEHICULAR ACTIVITY COMMUNICATION

LESSON LEARNED: Designers of future spacecraft communications systems should consider the following:

1. Speaker box placement and acoustical design should minimize speaker-to-microphone coupling.

2. Electronic gain changes resulting from signal level changes (automatic gain control (AGC) action) should be minimized.

3. Provision should be made for circuitry to disable speakers that could couple into a microphone whenever the microphone is keyed.

BACKGROUND: Skylab crewmen could not communicate effectively in the 5 psia atmosphere for distances exceeding 15 or 20 feet. The intercom box squeal and feedback problem kept crewmen busy adjusting boxes; some were finally turned off. The Skylab workshop audio system had 13 speaker intercom boxes. Only the speaker in the box with a keyed microphone was muted.

The Skylab 2 and 3 crews complained of extreme sensitivity to feedback and inability to adjust for an adequate uplink (received) volume level without being susceptible to audio feedback oscillation when a microphone was keyed for spacecraft-to-ground communication. For Skylab 4, a plug-in attenuator network was provided to optimize the intercom system electronic gain and to limit the AGC action.

S.L.L. No.: 2-34

TITLE: UNUSABLE VOLUME CLOSEOUTS

LESSON LEARNED: Closeouts around permanently installed hardware eliminated nooks and crannies into which loose items could disappear.

BACKGROUND: Skylab crewmen reported that the closeouts in the multiple docking adapter were helpful in keeping equipment from floating under equipment racks or behind control panels. These closeouts appear desirable when they can be provided without major impact.

S.L.L. No.: 2-35

TITLE: ACCUMULATION OF LOOSE ITEMS ON RETURN AIR VENTS

LESSON LEARNED: Virtually all loose debris (solid or liquid) in the orbital workshop migrated to the air mixing chamber screens in the dome. This phenomenon should be exploited in future designs by strategically locating the environmental return air vents and planning to collect loose items there. They should be easily cleanable or should have replaceable filters.

BACKGROUND: Skylab crewmen reported numerous instances in which lost items were found adhering to the screens. Conceivably, this feature could also be used for securing small items at workstations.

S.L.L. No.: 2-36

TITLE: NEED FOR SIMPLE IN-ORBIT RESTRAINTS FOR LOOSE EQUIPMENT

LESSON LEARNED: Many of the orbital workshop equipment restraints appeared to be oversized. Simpler concepts would have probably saved cost, weight, complexity, and crew time.

Operational equipment restraints should be standardized and should be simple and easy to use. Bungee-type restraints attached to stowage lockers, walls, doors, etc., would be adequate for many of the in-orbit equipment stowage and handling activities. Specific book restraints are needed at work sites to retain checklists and to keep them open to a given page. If a press-fit restraint is used for loose hardware, care must be taken not to insert the hardware too deeply or too tightly into the retention device. A specific means for keeping clothing spread out to dry while the crew sleeps would be desirable.

BACKGROUND: Massive launch restraint systems were used for some of the larger equipment items, and although they may have been necessary for launch, they were cumbersome to operate repeatedly in orbit. Some of the smaller equipment items were protected so well that they were almost inaccessible on short notice. For example, flashlights were packaged in individual Beta cloth bags inside an overbag, which was stored in a compartment within a stowage locker. Temporary stowage

capabilities are needed at use or interim locations to eliminate the need for returning items to their launch stowage containers. Most operational and experimental equipment requires an accompanying checklist, which necessitates the use of one hand if no checklist restraint is available.

S.L.L. No.: 2-37

TITLE: INTRAVEHICULAR ACTIVITY MOBILITY IN SPACECRAFT

LESSON LEARNED: Intravehicular activity architectural layout should ensure that normal translation routes do not interfere with the working, eating, sleeping, or relaxing crewmen. The critical point along a crewman's translation path is where he either changes direction or negotiates an opening such as a hatch. Attitude excursions are inherent at these junctures, and the lower extremities are constantly bumped on thresholds and hardware protruding around doorways. A buffer zone to minimize bumping should be used adjacent to all openings, and the immediate areas should be kept clear of protruding hardware.

In smaller compartments, like the crew quarters, the crew tended to position themselves perpendicular to the floor for normal activities and translation. This made the conventional arrangement of floor, ceiling, and lights useful. In large compartments, like the forward orbital workshop (OWS) dome area, the crew tended to translate head-first, because the walls and floor were not an influence.

BACKGROUND: The pilot's position at the wardroom table was such that to exit the wardroom he had to translate over the table or have another crewman move from his position to allow passage. Both methods were inconvenient, but passage over the table was also a hazard from the "foot-in-the-food-tray" point of view. Skylab crewmen impacted the OWS dome sufficiently en route to the dome hatch to leave dents in the ceiling. The crewmembers often bruised their legs as a result of multiple hatch negotiations and immediate attitude reorientations during the day.

In the crew quarters, the location of lighting on the ceiling and most equipment on the floor caused the crew to use a position perpendicular to the floor for translation and most activities. This tendency was reinforced by the availability of foot restraints on the floor. In the larger compartment, the crew did not adhere to the position perpendicular to the floor as much. They generally chose to move headfirst from one wall to another. Hence the compartment size and layout governed the preferred body orientation.

TITLE: USE OF SPACE IN HABITABLE COMPARTMENTS

LESSON LEARNED: Use of space in the smaller habitable compartments was very similar to use of space in Earth gravity. Overhead space was not particularly useful in orbit despite the increased ease of access.

BACKGROUND: It was expected that habitable compartment volume would be used more efficiently in zero-g space stations, because the space above one's head, which is of little use in Earth-based compartments, would be more useful in zero gravity. Possibly because of the particular architectural arrangement of the Skylab crew quarters, the crews were not inclined to use the space above tables and consoles or any space above their shoulder level when operating on the lower deck of the orbital workstation.

S.L.L. No.: 2-39

TITLE: HABITABLE ENVIRONMENT

LESSON LEARNED: The Skylab "comfort box" was acceptable. Temperature was comfortable, humidity was a bit low, acoustic environment was pleasant, and odors were virtually nonexistent. Portable fans are desirable. Individual thermal controls for sleep and waste management compartments would also be desirable.

BACKGROUND: Chapped lips, dry skin, and nasal discomfort were attributed to the low humidity experienced by the Skylab crews. Portable fans helped to relieve heat layers created by exercise and not dispersed by convection. Separate thermal controls for the waste management compartment would have allowed more comfortable bathing.

S.L.L. No.: 2-40

TITLE: HABITABILITY ILLUMINATION

LESSON LEARNED: The general lighting levels provided throughout the Skylab orbital assembly were marginally low but acceptable.

BACKGROUND: Subjective evaluations of the lighting levels provided in Skylab varied considerably among the crews of Skylab 2, 3, and 4. Skylab 2 and 3 crewmen frequently complained of insufficient illumination. Frequent use of a flashlight for supplemental lighting was

effective but inefficient and time consuming. Further, the waste management compartment overhead lighting made it difficult to obtain sufficient facial illumination for grooming and hygiene chores. The Skylab 4 crew felt that lighting throughout the cluster was adequate and did not present a problem, with one possible exception: they agreed with Skylab 2 and 3 crewmen that directional desk-type lamps would be desirable in sleep compartments, the wardroom, or any area where one would read or write.

S.L.L. No.: 2-41

TITLE: DESIGN "EYE" AND "REACH" ENVELOPES

LESSON LEARNED: If zero-g operation of a console or control panel is to be with foot restraint only, the design eyepoint should be an area with its center higher than the accepted one-g counterpart. Likewise, reach envelopes for zero-g workstations should be expanded from the seated one-g standard to a foot restrained zero-g standard.

BACKGROUND: The Skylab Apollo telescope mount (ATM) console became much more available to the crewman in zero gravity than it had been during seated one-g training sessions. Most Skylab crewmembers used foot restraints only when working at the ATM console.

S.L.L. No.: 2-42

TITLE: MANUAL DEXTERITY

LESSON LEARNED: The crewman's manual dexterity was not noticeably impaired by prolonged exposure to zero gravity. Intravehicular activities were performed with excellent dexterity throughout the missions; however, extravehicular activities continued to be hampered by the dexterity limitations of the suit and gloves.

S.L.L. No.: 2-43

TITLE: VISUAL GRAVITY VECTOR

LESSON LEARNED: In weightless conditions, architectural adherence to an up-and-down convention was found to be desirable as a convenience but not as a constraint.

BACKGROUND: The architecture of the Skylab orbital workshop was gravity oriented. This orientation permitted ease of ground testing and crew training. In flight, this convention provided the crew with a familiar coordinate system permitting easy orientation, location recognition, and equipment identification. The majority of crewmembers favored this architectural arrangement.

S.L.L. No.: 2-44

TITLE: STANDARDIZATION FOR THE DESIGN OF OPERATING CONTROLS AND DISPLAYS

LESSON LEARNED: There should be standardizations imposed on the design of all displays and controls used by the flightcrew (i.e., switches, indicator lights, control knobs).

BACKGROUND: The lack of uniformity in the light indicators for the different experiments comprising the Earth resources experiments package caused confusion to the crewmember operating the equipment. (For example, on one experiment the ready light went out while the equipment was in the calibration mode, while in a second case the light stayed on for the same mode of operation.)

REFERENCES: SC-D-007, General Specification for Displays and Controls for Manned Spacecraft and Related Flight Crew Equipment - Functional Design Requirements for, June 30, 1973; SC-M-003, General Specifications for Markings, Labeling, and Color, Manned Spacecraft and Related Flight Crew Equipment - Requirements for, November 18, 1971; SC-L-002, General Specifications for Lighting, Manned Spacecraft, and Related Flight Crew Equipment - Requirements for, July 25, 1972.

S.L.L. No.: 2-45

TITLE: CONTROL CONSOLE PROTECTION

LESSON LEARNED: Control consoles should not normally be located along major intravehicular activity crew traffic routes. When control panels are located in high traffic areas, bump-proof switch guards should be incorporated to preclude inadvertent switch actuations.

BACKGROUND: The airlock module/multiple docking adapter area of Skylab was a high-use passageway, yet the major spacecraft environmental control system and electrical power system controls and displays were located there. Instances of inadvertent switch or circuit breaker actuation occurred frequently because switches were bumped inadvertently or because the crew used existing panel guards as fingerhold mobility or restraint aids.

S.L.L. No.: 2-46

TITLE: CREW HANDWASHER DESIGN

LESSON LEARNED: Future design should have an enclosed handwasher that would allow hand insertion for working directly with the water.

BACKGROUND: Skylab's handwasher was not enclosed and consequently was used mostly to dampen a rag, which was then used "sponge fashion" to wash. After soap contacted the rinse rag, it was useless for further rinsing.

S.L.L. No.: 2-47

TITLE: SHOWER DESIGN

LESSON LEARNED: The shower bath concept of using a portable spray head in Skylab was satisfactory, but the method of water removal after use was not. The time and effort required to set up and take down the shower was inconveniently long.

BACKGROUND: The Skylab 2 crew showered as scheduled but complained about the mechanical inconvenience. They had favorable remarks to offer on the stimulating and pleasant experience that a weekly shower represented. The Skylab 3 crew retreated to sponge baths with washcloths in lieu of using the time required to erect, use, clean, and disassemble the shower. Had it been more convenient, they would have used it. However, the washcloth sponge bath was deemed "adequate" by the Skylab crewmen.

TITLE: SLEEP STATION DESIGN

LESSON LEARNED: Sleeping against the wall was acceptable in zero gravity. Sleep stations should be insulated from outside light and noise as much as possible. Sleep compartment ventilation should flow in a head-to-foot pattern, not "up the nose." Flexibility in blanket arrangements should also be provided to accommodate varying thermal conditions.

The sleep restraint concept was basically satisfactory; however, there should be more restraint against the firm back than just the straps provided for Skylab. The straps were strong enough but did not cover a sufficient amount of body area.

BACKGROUND: Skylab crews slept satisfactorily in the erect against-the-wall orientation, and the only relocation of sleep facilities was attributable to environmental rather than psychological factors. Both temperature and airflow triggered sleep restraint reorientations or relocations. Skylab crews were extremely sensitive to auditory disturbance while attempting to sleep. Illumination stimuli were more controllable than noise.

S.L.L. No.: 2-49

TITLE: USE OF PROPRIETARY HARDWARE

LESSON LEARNED: Care should be exercised when using proprietary end items. If no nonproprietary item can be substituted, the proprietary item may be accepted through a waiver process. In such cases, the item should be disassembled to identify components and materials, or the manufacturer should be required to provide this information for government use only. These constraints relative to the use of proprietary items should also be levied against subcontractors by prime contractors.

BACKGROUND: The use of proprietary items as parts of space hardware has frequently resulted in the use of unreliable components and unacceptable nonmetallic (i.e., flammable and toxic) materials. Failures of flight hardware have been caused by components that were not known to be internal to proprietary assemblies. Examples include the Malaker cooler used on the S191 infrared spectrometer and the sealed power supply used on the S071/S072 vinegar gnats/pocket mice circadian rhythm experiment.

S.L.L. No.: 2-50

TITLE: EXPERIMENTS INPUTS NEEDED FOR SIMULATOR DESIGN

LESSON LEARNED: During the development of experiment simulations for crew training, there must be good communications between the experiment experts and the simulation engineers.

BACKGROUND: Throughout the production of solar image, corona, and radiation simulations for the Apollo telescope mount displays of the Skylab simulator, a team consisting of the Principal Investigators and their colleagues advised the simulation engineers on the solar image renditions. The good communications provided the feedback necessary to assure the high fidelity rendition of image simulations required for valid training.

S.L.L. No.: 2-51

TITLE: AVOIDING STRESS CORROSION

LESSON LEARNED: Designers should be conscious of stress corrosion and should design specifically to avoid it. The use of ferrous or aluminum alloys susceptible to stress corrosion should be specifically avoided.

BACKGROUND: A considerable amount of time and money was spent in surveying Skylab hardware for materials susceptible to stress corrosion and in surveying the applications of these materials. Hardware inspections and modifications to hardware were also required to eliminate potential stress-corrosion problems.

REFERENCE: Stress-Corrosion Cracking in Metals, NASA SP-8082, August 1971.

S.L.L. No.: 2-52

TITLE: REDUNDANT SYSTEMS SHOULD ALLOW CONCURRENT OPERATION IF DESIRED

LESSON LEARNED: Redundant systems and, in some cases, redundant components should be designed to be capable of operating at the same time. This approach would allow use of two systems or components if one were marginally acceptable. The lack of this capability caused difficulty in operating several Skylab systems after failures or anomalies occurred in orbit.

BACKGROUND: The orbital workshop refrigeration systems temperature control valves (one valve in each of the two systems) had similar failure indications (sticking). Whereas initially, cooling was adequate with the operation of one nominal system, following system failure (i.e., sticking valve), sufficient coolant could be passed through the heat radiator only if both refrigerant systems were operated at the same time. Also, failure of one of four pumps in a system, indicated by low delta pressure, could be analyzed by running two or more pumps at the same time in lieu of turning on each pump separately in a single system. The latter procedure would risk temporary system shutdown if a malfunctioning pump were encountered.

S.L.L. No.: 2-53

TITLE: ONBOARD SPACECRAFT EXPERIMENT DATA READOUT

LESSON LEARNED: Onboard experiment data readout and assessment capability should be designed into all future manned spacecraft. This would allow the crewman to assess the experiment performance and thus optimize experiment data taking as well as crew operational time.

BACKGROUND: Some experiment data collected on Skylab 2 and 3 were unusable because of equipment malfunction, errors in calibration, or improper setup. Experiment test data on the ground could be compared to sample onboard data for gross determination of acceptability.

S.L.L. No.: 2-54

TITLE: DESIGN OF CONTROLS AND DISPLAYS FOR EXPERIMENTS

LESSON LEARNED: The Apollo telescope mount (ATM) panel was divided by experiment groupings. Operations would have been improved considerably had the groupings been configured by function (i.e., thermal, power, initialization, start, stop, etc.). (The S052 thermal was inadvertently turned off by the crew because of its proximity to other frequently operated switches.) Also, the logical operational sequences should be considered and a programer provided that would initialize and then start the experiments sequentially, as applicable, by the manipulation of a minimum of controls. In the case of ATM-type experiments, the logic could be programed by using the building blocks and/or joint observation programs. The capability to alter the programer in real time with a minimum of effort would be necessary. The use of a programer to control the experiments would leave more of the crewman's time for scientific evaluation and observation.

BACKGROUND: During ATM operations in orbit, a very large fraction of the crew time was devoted to throwing switches and very little time to analyzing the experiment data for its usefulness and quality. Also, a considerable amount of crew time was devoted to changing the crew checklists of the joint observations project (JOP) summary sheets. If the JOP's had been programed in a computer and a ground uplink provided to change the program, a greater percentage of crew time could have been used for analysis and evaluation of the data being observed.

NOTE: At the time the ATM control and display panel was designed, representatives from both the NASA Lyndon B. Johnson Space Center and the NASA George C. Marshall Space Flight Center collaborated on what appeared to be the best design approach. The experience gained during the Skylab missions pointed out potential improvements in design philosophy.

S.L.L. No.: 2-55

TITLE: EXPERIMENT HARDWARE DESIGN

LESSON LEARNED: Criteria governing the design of experiment hardware override should include ease of operation, spacecraft interface, manual override, and maintainability as well as those requirements dictated by the scientific objectives.

BACKGROUND: The scientific gains from any experiment are dependent not only on the hardware used to measure scientific phenomena but also on the crewman's ability to operate the equipment. With several corollary experiments, the first few operational periods were totally lost because the crewman could not correctly operate the equipment. Whereas this may reflect on training, the designer should be aware that the crewman may receive very little training in his flight preparation. The hardware design should include easy assembly and simple controls. Several Skylab experiments were lost because there was very little, if anything, that could be done to repair the hardware or to use it in a degraded mode. In one particular case, the experiment was jettisoned from the workshop because there was no way to manually override the malfunctioning electronics.

S.L.L. No.: 2-56

TITLE: EXPERIMENT SYSTEM CONTROLS

LESSON LEARNED: Simplicity of operations should be a primary design objective in integrated experiment facilities. Specific conditions to avoid are:

1. Logic race conditions that impose time-delay constraints on switch actuations by the crew.

2. Requirements for multiple switching operations to accomplish a single system mode change.

3. Multiple system controls that include numerous invalid modes in the various permutations of switch settings.

4. Requirements for specific switching sequences and timing to avoid critical data losses due to tape recorder speed changes.

BACKGROUND: The operation of the Earth resources experiment package from the control and display panel was so complex that it required an inordinate amount of time in preparing error-free switching time lines and then required the complete attention of the operator to execute the time line successfully. The S193 experiment system was the primary troublesome area with numerous switching constraints imposed to avoid logic race problems or invalid modes.

S.L.L. No.: 2-57

TITLE: SPACE EXPERIMENT SYSTEMS MONITORING CAPABILITY

LESSON LEARNED: Space experiment systems intended for operation on a repetitive basis should incorporate sufficient monitoring capability to verify proper system operation. Although corrective measures may not always be anticipated before flight, some method of recovering at least partial capability can usually be devised if a problem is recognized.

BACKGROUND: The Earth resources experiment package (EREP) systems monitoring capability was severely limited, as follows:

1. The information available in real time was provided by status lights and a few analog meters. The status lights were not always interpreted properly and the crewman generally had inadequate time and

detailed systems knowledge to use the displayed analog data effectively.

2. Near-real-time data were available when the EREP diagnostic downlink unit (EDDU) was used, but because of the impact of data-support schedules, its use was restricted to the diagnosis of problems after identification.

3. In the absence of data for confirming satisfactory experiment operation on a routine basis, experiment accomplishments during the mission were estimated, pending postmission assessment of the system performance and data quality.

S.L.L. No.: 2-58

TITLE: USE OF COMMON SYSTEMS FOR MULTIPLE EXPERIMENTS

LESSON LEARNED: Operational constraints and/or capabilities should be considered before using a common system for more than one experiment.

BACKGROUND: A common power system was used for the S052 and S054 Apollo telescope mount experiments to drive the aperture doors. S054 had a very wide field of view with no constraints on pointing off the solar disk, while S052 was constrained to pointing at the center of the Sun. Removing power from the door motors to maintain the S054 doors in the open position following a mechanical anomaly jeopardized S052 operations.

S.L.L. No.: 2-59

TITLE: EXPERIMENT DESIGN - AUTOMATIC CONTROL LIMITS

LESSON LEARNED: Automatic control limits should be based on measurements of the critical condition, not on an intermediate computation.

BACKGROUND: The S055 experiment had a pointing limit designed into the Apollo telescope mount digital computer. This limit closed the door when the pointing exceeded a predetermined value from Sun center. The limit was derived from the fine Sun sensor wedges that commanded the pointing system. The wedges only showed the desired pointing command so that the resulting S055 limit was often invalid.

S.L.L. No.: 2-60

TITLE: FILM AND MAGNETIC TAPE USAGE MEASUREMENTS

LESSON LEARNED: Accurate, reliable indications of the usage of film and tape consumables are necessary for effective consumables management and for proper data-recording verification.

BACKGROUND: The photosensitive strip tape-remaining instrumentation provided for the Earth resources experiment package tape recorder was too unreliable to be used because of nonlinearities and temperature sensitivity. The use of a manual measuring technique on the tape reels proved much more effective.

The film remaining indicator on the 140-foot data acquisition camera (DAC) magazines was unreliable, with depletion normally occurring with the indicator still showing more than 20 percent remaining. This severely limited the effectiveness of managing the viewfinder tracking system DAC film and of assessing the film coverage acquired.

S.L.L. No.: 2-61

TITLE: EXPERIMENT DATA IDENTIFICATION, RECORDING, AND TELEMETERING

LESSON LEARNED:

1. Spacecraft experiment data should be identified to aid in ground data processing.

2. No single experiment should require more than one spacecraft recorder at a time to record data.

3. When telemetering experiment data, not more than one downlink should be required for a single experiment.

BACKGROUND: In Skylab, data from several experiments were mixed with other experiment or operational systems data and no experiment identification was included in the data. This increased the complexity of the ground software task of data processing. Some biomedical experiment data were recorded on two separate recorders, which required the processing of two separate dump tapes. This compounded the ground data retrieval problem, synchronization requirements, and doubled the effect of data dropouts on experiment data.

S.L.L. No.: 2-62

TITLE: EXPERIMENT INSTRUMENT ALINEMENT SYSTEMS DESIGN

LESSON LEARNED:

1. Each telescope should have its own independent alinement and pointing system. If a group of telescopes is used, an additional means of pointing them as a group should be provided.

2. In-flight co-alinement of similar instruments should be provided. The problems associated with ground co-alinement in a one-g environment were significant and such a capability would lessen the structural requirements of a rigid platform (optical bench).

BACKGROUND:

1. Within the Apollo telescope mount (ATM) experiments, there were three large field-of-view (FOV) instruments, two small FOV instruments requiring precise pointing, and one instrument that could only operate while pointed at the Sun's center. Therefore, the only time all instruments could operate simultaneously was at Sun center, an area of little activity compared to the remainder of the solar disk. In addition, the alinement between the two small FOV instruments was to satisfy both groups of Principal Investigators. These factors often resulted in one or more instruments dropping out of a joint observation program because the pointing was not optimum. This was particularly apparent near the end of Skylab 3 when film was running short and investigators chose to omit their instruments rather than accept marginal data for less than optimum pointing.

2. Experiments S082B and S055 were alined before launch; however, during the mission, the S082B slit was 105 arc seconds above the center of the S055 raster pattern.

S.L.L. No.: 2-63

TITLE: DESIGN OF ZOOM TELESCOPES FOR INSTRUMENT POINTING

LESSON LEARNED: Variable magnification telescopes intended for use as precise pointing aids for sensors should be designed with the optical axis of the zoom lens precisely alined with the optical axis of the

sensor. Any in-flight alinements necessary should be accomplished by
adjusting the zoom lens with integrated reticles rather than by merely
adjusting reticles apart from the lens. If specific zoom position is
a factor in pointing control or data evaluation, the zoom setting
should be instrumented.

BACKGROUND: The S191 experiment viewfinder tracking system telescope
was designed with adjustable reticles in the optical path between the
zoom lens and the viewing port. In-flight alinement capability was
provided by using a lighted cross and a sensor signal acquisition in-
dicator by adjusting the reticle position. Because of a disparity
between the optical axis of the instrument and the optical axis of the
zoom lens, the resultant alinement was valid only at one zoom setting.
This imposed an undesirable operational constraint in that data taking
had to be conducted at the zoom setting used for alinement. There was
no indication provided for zoom position except at the stops.

S.L.L. No.: 2-64

TITLE: REVIEW OF MULTIWORD COMPUTER UPLINKS

LESSON LEARNED: Future spacecraft systems capable of receiving multi-
word command loads for use by spacecraft software systems should have
prestorage buffer viewing capability. This permits ground or onboard
viewing of the information before its placement in the software working
memory.

BACKGROUND: This was a valuable capability in the command module com-
puter and the lunar module software, virtually eliminating the likeli-
hood of incorporating erroneous data. This capability was provided to
a limited extent in the Apollo telescope mount digital computer but not
in the launch vehicle digital computer. The lack of this capability
caused concern during the Apollo translunar insertion navigation update
and Skylab prelaunch rendezvous targeting experiences. In both situa-
tions, extensive planning and procedural efforts were required to mini-
mize the possibility of incorporating incorrect data.

S.L.L. No.: 2-65

TITLE: EXPERIMENT DATA SYSTEM DESIGN

LESSON LEARNED: Future manned space experiments should avoid instru-
ment design that submultiplexes all parameters into one digital word.
Parameters indicating the commanded state should be downlinked in
real time.

BACKGROUND: One of the problems encountered on Skylab was associated with the command and service module (CSM) spectrometer. This instrument had five detectors that measured electrons in four channels and protons in five channels. In addition, these were "housekeeping" measurements indicating the operational status of the electronics and the detectors. All these parameters were submultiplexed internally in the instrument into a 13-bit digital word. This design presented the following problems:

1. Detector power was turned off on several occasions during which ground control was not informed of the action for an average of 3 days while data were being processed off line at another location at the NASA Lyndon B. Johnson Space Center. The problem occurred because the spectrometer did not have real-time data. Decoding the digital word required special processing.

2. Instrument operational status could only be monitored on a near-real-time basis with a turnaround time of several days.

3. The CSM spectrometer was a crew health item (i.e., used for radiation monitoring) and, therefore, the lack of real-time data from the instrument presented a problem in analyzing the true radiation hazard to the crew.

S.L.L. No.: 2-66

TITLE: WAVEGUIDES INSTALLATIONS

LESSON LEARNED: If flex waveguide sections are used as an aid to alinement in complex waveguide assemblies, particular attention should be given to additional support in the immediate area of the flex sections. One particularly good solution may be the addition of supports (or splints) that provide redundant load paths to the flex sections.

BACKGROUND: Several cracks in flex sections of the S193 microwave/ radiometer/scatterometer experiment were caused by system level qualification vibration testing. These cracks were prevented by the addition of support brackets and by redundant load paths, as noted above.

S.L.L. No.: 2-67

TITLE: CONDUCTIVE ELEMENT POTENTIOMETER APPLICATION

LESSON LEARNED: When conductive-element-type potentiometers are used
and when the potentiometer is not provided with its own housing, par-
ticular attention should be given to providing protective shielding
(or sealing if at all possible) to provide protection from external de-
bris that could cause shorting of the conductive element to ground or
to some other circuit.

BACKGROUND: In the late stages of the Skylab 3 mission, the S193 micro-
wave/radiometer/scatterometer experiment lost control of the antenna
scan. This condition was subsequently partly corrected by clearing
stray conductive debris from the antenna position potentiometers during
an extravehicular activity (EVA).

S.L.L. No.: 2-68

TITLE: USE OF SWAGING TECHNIQUE IN LIEU OF "Z" WIRES ON PRINTED
        CIRCUIT BOARDS

LESSON LEARNED: It is recommended that a swaging technique be used
instead of "Z" wires as interfacial connections through plated-through
holes in printed circuit (PC) boards. The technique uses a Utica Drop
Forge swaging tool, Model 470-5 or equivalent, to form a wedge on both
sides of a piece of copper wire inserted through the plated-through
hole. This technique offers the following advantages over "Z" wires:

1. Easier and faster installation

2. Less damage to printed wiring circuits because of tool slippage,
    sharp wire edges, etc.

3. No rework because of "Z" wires turning away from the circuit pat-
    tern during flow soldering

4. Simplified rework for removal of the through connector

5. No decrease in effectiveness of the interconnection

BACKGROUND: Rework of any printed wiring connection necessitates the application of heat and some force to effect component replacement on PC boards. During rework of the S194 printed wiring boards, a combination of these factors caused lifted lands when the tolerance of the land to adhere to the board was exceeded. The lands lifted when "Z" wires were removed to allow the addition of hard wires for engineering changes. The swaging technique, which subsequently proved very successful, was implemented to facilitate PC board changes and to prevent lifting of the land.

SECTION 3

DESIGN PRACTICE

S.L.L. No.: 3-1

TITLE: FLIGHTCREW DISPLAYS OF SYSTEM STATUS

LESSON LEARNED: If more than one method (i.e., switch, crew keyboard and/or ground command) is provided for accessing an onboard function, a dedicated indicator, such as a talkback, must be provided to display the current configuration.

BACKGROUND: In some cases, Skylab used latching switches to indicate system configuration. If the configuration was subsequently changed through the digital address system (DAS) or ground command, the crew had no indication of systems configuration. This required extensive ground/crew coordination, and in some cases, a special sequence of "unnecessary" ground commands was required to be sent to ensure that hardware functions matched onboard switches.

S.L.L. No.: 3-2

TITLE: TAPE RECORDER STATUS INDICATIONS AND COMMAND REQUIREMENTS

LESSON LEARNED: Indications should be provided to show onboard recorder operation relative to selection, tape remaining, and recording status to both the crew and the ground.

Minimize the number of commands required for such routine functions as tape recorder management. Design recorders such that redundant data are not dumped and implement transducers that provide maximum information.

BACKGROUND: If onboard data recorders are crew operated and ground dumped, then the system should be designed to show tape position, record initiation time, total record time, if rewound, etc. This has always been a guessing game in the past.

The command module data storage equipment required far too many commands for a routine dump. The Skylab Apollo telescope mount recorders necessarily dumped redundant data. The crew was excessively inconvenienced, and flight plan activity was impacted because the crew did not have sufficient status information relative to the data/voice recorder. An indicator of the time remaining on all the recorders, especially the video tape recorder, would have helped a great deal.

58

TITLE: REALISTIC TOLERANCES

LESSON LEARNED: Care should be exercised to avoid the establishment of impractical tolerances. If this is not done, the quality assurance workload will increase because specifications will not be met and each nonconforming item will have to be identified and material review board actions will have to be initiated.

BACKGROUND: Excessively tight tolerances were established for some experiment designs. Numerous waivers were processed against tolerance requirements, which probably could have been relaxed for a more cost-effective solution to the situation.

TITLE: ELECTRICAL AND FLUID CONNECTOR DESIGN

LESSON LEARNED: Fluid line and electrical connections should be designed and labeled to preclude incorrect mating.

BACKGROUND: Experience dictates that in mating fluid lines or electrical connectors, it is possible to cross connect (or reverse) the connections (e.g., fill as opposed to drain, reaction control system as opposed to fuel, positive as opposed to negative, and pressurize as opposed to bleed). Such items as plugs, disconnects, and couplings should be designed to preclude connections that are not intended.

TITLE: SPACECRAFT GLASS WINDOW DESIGN

LESSON LEARNED: Fracture mechanics should be used as the principal method of evaluating spacecraft glass structural designs and of specifying the proof tests required to verify the safety of the design. Proof tests should be conducted in an inert environment, particularly one free from moisture, to ensure that the glass flaws do not grow during the proof testing. Test evaluation criteria must also include infrared (IR) and ultraviolet (UV) radiation considerations. The pressure seal backup capability for single-pane windows should be verified as adequate for crew protection in the event of rapid decompression due to window failure.

BACKGROUND: Glass strength degrades with time because of a combination of stresses in certain environments, of which moisture is recognized as the most detrimental. Some flaws are always created during the manufacturing process but are generally not detectable by any known method other than proof testing based on fracture mechanics analyses. This method was used to evaluate both the command and lunar module windows. Structural design requirements must consider the possible degradation effects of exposure to space radiation on both the optical and structural properties of the windows. In addition, the glass should not transmit into the crew habitation area either UV or IR radiation, which might affect the crew's health or actuate UV fire sensors.

REFERENCE: Apollo Experience Report - Spacecraft Structural Windows, NASA TN D-7439.

S.L.L. No.: 3-6

TITLE: USE OF DISSIMILAR METALS IN ELECTROLYTE FLUID SYSTEMS

LESSON LEARNED: The use of dissimilar metals should be avoided in fluid systems in which electrolytic solution exists in the plumbing. Both the drawings and hardware should be visually inspected in systems in which the potential for such problems exists. If electrons must be conducted into the structure (i.e., when the vehicle structure is used as an electrical conductor/ground return), an analysis should be performed as a first step to determine their effects on corrosion of joints of dissimilar metals.

BACKGROUND: The coolant loop used for the Skylab Earth resources experiment package (EREP) tape recorders consisted of water with inhibitors to control corrosion within the loop. Stainless steel and aluminum were used at several joints. The system was tested under conditions similar to those expected in flight. The tests results showed that the system should be satisfactory for flight; however, a large amount of residue in the form of aluminum phosphate ($AlPO_4$) was found in the filters during prelaunch inspections. A further complication was that the circuits within the EREP tape recorder used a structural ground (although a waiver was granted to permit this design to save large costs of redesigning). The path of the current was, in part, through the dissimilar metal joints of the coolant system. Variations in electrical resistance across the dissimilar metal in the order of milliohms could drive aluminum ions into the coolant solution. A chemical reaction with the inhibitors was thought to have caused $AlPO_4$ to form at the joint because of the current through the joint.

A review of the detailed manufacturing drawings showed that dissimilar metals existed in many more places than were previously documented in the design.

REFERENCE: JSC Criteria and Standard DS-63 on usage of dissimilar metals.

SECTION 4

DEVELOPMENT

S.L.L. No.: 4-1

TITLE: PRESSURE CONTROL UNIT MALFUNCTION SIMULATOR

LESSON LEARNED: The pressure control unit (PCU) malfunction simulator proved to be an invaluable tool for training the Skylab crews on basic PCU operations, extravehicular mobility unit (EMU) malfunctions and their corrective actions, and mission rules and philosophies. The simulator also built up the crew's confidence in the operation of the EMU hardware.

A simulator of this type should be mandatory for all future missions where extravehicular activity (EVA) operations are involved.

BACKGROUND: A simulator of this type was requested several times during the Apollo Program but was rejected on the basis of cost, time, etc. Although Apollo crew training involved several Earth gravity walkthroughs, vacuum chamber tests, etc., the crew's confidence in the EMU hardware and associated malfunction procedures was not at the Skylab level until very late in the program. A simulator of this type allows the crewman to sit calmly at a desk, in a shirt-sleeve environment, and devote all his attention to each system's operation and malfunction as opposed to trying to gain the same knowledge by a walkthrough or chamber test involving other support personnel and based on a strict time line.

S.L.L. No.: 4-2

TITLE: OPERATIONS INPUTS TO SYSTEM DEFINITION AND DEVELOPMENT

LESSON LEARNED: Operations personnel need to be involved in the definition and development phases of a manned space-flight program.

For future programs, at both the contractor facilities and within NASA, the organizational structure should provide for an adequate flow of experience and coordination from operational elements to the engineering design and test groups during the definition and development phase. Conversely, during the operational phases, direct participation of designers should be assured.

BACKGROUND: In developing malfunction procedures for a system that has already been designed, it frequently becomes evident that the system is deficient in onboard controls and displays for rapid failure isolation by the crew. As a result of these deficiencies, the isolation of the

failure becomes a long cumbersome process and, in some cases, the failures cannot be isolated. Participation by operationally experienced personnel in the early design review activities tends to uncover these design deficiencies while corrective action is possible with minimum impact.

S.L.L. No.: 4-3

TITLE: EVALUATION OF DEVELOPMENT HARDWARE BEFORE BUILDING FLIGHT HARDWARE

LESSON LEARNED: Flight hardware should not be built before adequately evaluating breadboard and development verification test unit (DVTU) models.

BACKGROUND: In the development of M171 metabolic analyzers, the flight unit was built and stowed in the orbital workshop before the DVTU was delivered for physiological testing and verification. During laboratory testing, several design inadequacies were uncovered that impacted the flight hardware and forced retrofits at additional expense to the Government.

S.L.L. No.: 4-4

TITLE: EQUIPMENT PERFORMANCE SPECIFICATION AS OPPOSED TO SCIENCE REQUIREMENTS

LESSON LEARNED: Before scientific hardware programs are implemented, the scientific requirements should be made compatible with the technical performance criteria and well defined relative to whether the performance criteria are within the bounds of the present-day technology.

BACKGROUND: The Skylab Earth resources experiment package science hardware evolved from scientific requirements based on theoretical values derived from the natural sources under investigation. These criteria were used as stringent requirements for equipment performance. In many instances, the equipment could not meet these goals. For future programs, the relevance of the scientific requirements to what is necessary and obtainable should be evaluated before equipment is developed. Tradeoffs of scientific desirability as to what is technically achievable should be made when the preponderance of desired data can be achieved within the present state of the art. For instance, an instrument resolution to $1^{\circ}K$ should not be specified as the absolute limit when $1.5^{\circ}K$ is adequate.

Theoretical scientific requirements should be questioned, justified, and incorporated into technical performance specifications only after they have been fully evaluated. Consideration also should be given for an incentive-type technical specification in those areas in which the present state of the art will not meet the desired objectives.

S.L.L. No.: 4-5

TITLE: SPACE APPLICATION OF HIGH-DENSITY DIGITAL TAPE RECORDER

LESSON LEARNED: Multitrack stationary-head recording techniques can be used to satisfy high-data-rate/high-data-storage capacities required by spaceborne Earth resources experiments.

BACKGROUND: The Skylab Earth resources experiment package (EREP) tape recorder system recorded data rates of approximately 1 Mbps on 24 tracks at 60 in/sec and 60 kbps on two tracks at 7.5 in/sec and 60 in/sec; it recorded a frequency modulation composite consisting of inertial reference integrating gyro (IRIG) channels 13, B and D on two tracks at 7.5 in/sec and 60 in/sec. The total was 28 tracks on 1-inch-wide magnetic tape. The developed data-storage capacity was approximately 4.8×10^{10} bits/magnetic tape pack; the equipment was qualified at approximately 3.8×10^{10} bits/tape pack, and it was used in Skylab at approximately 3.5×10^{10} bits/tape pack. The bit error rate requirement was 5 in 10^6. This was the first known application in space of a data packing density of 17 000 bpi/track on magnetic tape. This hardware is adaptable to other space applications.

REFERENCES: MSC-03143, Development Test Report for EREP Tape Recorder; MSC-05352, Test Report for EREP Magnetic Tape Evaluation Test Programs.

SECTION 5

PARTS AND MATERIALS SELECTION

TITLE: CONSIDERATIONS FOR USE OF OFF-THE-SHELF ITEMS

LESSON LEARNED: Designers should consider the use of commercially available parts and materials as a routine practice when procuring new hardware. There is always the option of using local vendors, as well as that of securing competitive bids, when fabrication of noncritical hardware is involved.

Some recommended guidelines for the use of off-the-shelf hardware are as follows:

1. Materials testing of off-the-shelf items should focus on the specific application and generally should be nondestructive.

2. Nonflammable covers, when used, can preclude costly redesign of internal items for flammability reasons.

3. Off-the-shelf hardware should be disassembled and visually inspected as part of the evaluation procedure before use. Reliance on the contractor's inspection stamp and/or acceptance test results is not always sufficient, as the documentation below illustrates.

BACKGROUND: The NASA Lyndon B. Johnson Space Center (JSC) used off-the-shelf hardware for the contents of the science demonstration kit, for the contents of the pressure garment assembly maintenance kit, for hand exercisers, etc. When certifications appeared to be unwarranted, appropriate waivers were executed. The orbital workshop firehose was a Sears item covered with a Beta material.

The S071/S072 experiment on Skylab failed because of poor packaging of an off-the-shelf inverter. Three off-the-shelf inverters that displayed the vendor's inspection stamp were tested to reasonable requirements. The inverters were subjected to variable thermal vacuum mission profiles, and test results indicated that the hardware was ready for flight. Subsequent to failure testing and analysis following the mission, the two remaining inverters were opened for inspection. Conductors in several places were very nearly exposed; in those instances where wires were exposed (i.e., insulation was missing), a piece of tape had been used to provide insulation from the metal case. In many areas, there were also signs of charring of the potting material caused by arcing from the conductors to the case, yet the inverters had passed all previous tests. This failure could have been avoided if the inverters had been disassembled and visually inspected before use.

REFERENCES: JSC Policies and Procedures; JSCM 8080 Criteria and Standards; and WA-076 Memorandum, Beware of Off-the-Shelf Hardware, October 17, 1973.

S.L.L. No.: 5-2

TITLE: PASSIVATION OF INTEGRATED CIRCUITS

LESSON LEARNED: Passivation of integrated circuits as a standard requirement for high reliability integrated circuits should be investigated early in a program. Cost tradeoffs should then be made before implementation of blanket requirements.

BACKGROUND: Failures during qualification level vibration testing occurred during the Skylab Program (e.g., M093 vectorcardiogram: operational amplifiers) when metallic contamination inside the integrated circuit shook loose and shorted adjacent traces. Passivation of the die would have prevented most of these failures.

S.L.L. No.: 5-3

TITLE: PROCUREMENT OF ITEMS COMMON TO MORE THAN ONE CENTER

LESSON LEARNED: Separate Center and contractor procurements of the same or similar items should be avoided, because this approach can result in several specification number or part number callouts for the same item. Common requirements for the same item by more than one Center or contractor should be coordinated, and the commonality aspects should be managed to the advantage of the program.

BACKGROUND: The NASA George C. Marshall Space Flight Center (MSFC) developed and provided basic zero-g connector specifications. Zero-g connectors were required for power cables, jumpers, utility cables, camera cables, television cables, etc. Initially, several specification numbers and part numbers were created to specify the same zero-g connector. Total program inventories on connectors were difficult to obtain, and multiple procurements were conflicting.

The NASA Lyndon B. Johnson Space Center (JSC) zero-g connector procurement was consolidated by the Program Office, and the purchase request had a feature added that stated that any MSFC engineering order changes to the basic specification were applicable to JSC procurements. This accelerated JSC procurement and allowed application of coordinated allocation and priorities for items in short supply.

SECTION 6

MANUFACTURING

S.L.L. No.: 6-1

TITLE: CONFORMAL COATING OF DUAL IN-LINE PACKAGE INTEGRATED CIRCUITS

LESSON LEARNED: An overly thick layer of conformal coating under the body of the dual in-line package caused cracking of the package under thermal cycling.

BACKGROUND: Some Skylab experiments (i.e., M092 and the Earth resources experiment package) experienced cracking of the dual in-line packages, which was traced to thermally-induced stresses between the conformal coating and the package. After the thickness of the coating was reduced, no further cracking problems were encountered.

SECTION 7

TEST

S.L.L. No.: 7-1

TITLE: PRELAUNCH CHECKOUT

LESSON LEARNED: Space vehicle systems should be checked out to the end-item. Instead of verifying that a piece of equipment draws "x" amperes when power is applied through a switch, the proper piece of equipment controlled by that switch should be verified as operative.

BACKGROUND: The Skylab 3 command and service module hydrogen tank heaters and fans were miswired. When the crewman actuated the hydrogen tank 1 heaters and fans, the hydrogen tank 2 heaters and fans came on, and vice versa. This miswiring was not detected in prelaunch checkout.

S.L.L. No.: 7-2

TITLE: ACCEPTANCE TESTING OF BIOMEDICAL HARDWARE

LESSON LEARNED: All biomedical hardware should be in accordance with its designated experiment requirements.

BACKGROUND: Early qualification and acceptance testing of the M171 metabolic analyzer was inadequate because no manned tests were included. The metabolic analyzer functioned adequately with a mechanical pump, but it did not perform adequately with a human subject at rest or performing exercise. Specifically, the electronic trigger for the spirometers functioned well with a sine-wave mechanical pump but false triggered when subjected to human respiratory patterns.

S.L.L. No.: 7-3

TITLE: COMMONALITY OF GROUND SUPPORT EQUIPMENT

LESSON LEARNED: Identical sets of ground support equipment (GSE) should be used at each location where preinstallation acceptance (PIA) testing is to be done, and these should be identical to those used for initial in-plant predelivery acceptance. Seemingly innocuous changes in instruction, pressure gage ranges, plumbing, and procedures can cause confusing and sometimes erroneous indications of hardware performance.

BACKGROUND: The Gemini Program pointed out very graphically that changes in the GSE affect interpretation of hardware performance. The extravehicular life support system GSE used at the NASA John F. Kennedy Space Center (KSC) for preflight PIA differed markedly from that used at the contractor's establishment and at other sites. Rotameters were used instead of laminar flow elements; procedures varied;

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and locations in the system where critical performance parameters were sensed also differed for arbitrary reasons. It was not until just before Gemini XII that the full extent of and reasons for differences in test philosophy, results, etc., were finally understood. In the Skylab Program, definite attempts were made to use the same GSE at the contractor's establishment, at the NASA Lyndon B. Johnson Space Center, and at the KSC. The attempts were successful, and the only differences in equipment involved peculiarities of the gas supply systems and the vacuum systems. Thus, test results could be discussed more universally between sites.

S.L.L. No.: 7-4

TITLE: DOCUMENTATION REQUIREMENTS FOR QUALIFICATION AND ACCEPTANCE TEST PLANS

LESSON LEARNED: Do not levy the requirements of Sections 4.0, Exhibits II (Prime Equipment) and IV (Identification Items), Parts I and II of NASA Procurement Circular (NPC) 500-1 or NASA Handbook (NHB) 8040.2 on suppliers or manufacturers of end-items. The Qualification Test Plan and Acceptance Test Plan, respectively, will satisfy these requirements.

The contract end-item specifications can be simplified by eliminating Section 4.0, Parts I and II of Exhibit I and IV of NPC 500-1 or NHB 8040.2. These requirements can be combined with those of the Qualification Test Plan (Part 1) and Predelivery Acceptance Test Plan (Part II). Both 4.0 sections are redundant with the plans and only increase contract cost.

BACKGROUND: The contract end-item specifications, Parts I and II, contain primiarily five sections. Section 3.0 of both parts is requirements, and Section 4.0 of both parts is test/verification of the requirements listed in Section 3.0. Sections 3.0 and 4.0 of Part I form the basis for the Certification (Qualification) Test Plan. Likewise, Sections 3.0 and 4.0 of Part II form the basis for the Acceptance Test Plan. Both of these plans are type I and are under formal changeboard control.

The data contained in both Section 4.0's - specifically, paragraphs 4.1 and subsequent paragraphs - are repeated in the pertinent test plans and are thus redundant. Both of the Section 4.0's are thoroughly reviewed against the applicable Section 3.0.

Deleting paragraphs 4.1 and subsequent paragraphs of both Section 4.0's results in the following advantages:

1. A change to either Section 3.0 requires only one additional change (to the plan), not two (the plan and Section 4.0).

2. The thorough review previously applied to Sections 3.0 and 4.0 and to the plan versus Section 4.0 would be applied only to the plan versus Section 3.0.

3. Redundancy is eliminated.

S.L.L. No.: 7-5

TITLE: MANNED ALTITUDE TESTING OF EXPERIMENT AND SPACECRAFT SYSTEMS

LESSON LEARNED: Manned altitude chamber tests that simulate critical mission sequences should be conducted on equipment sensitive to operation at reduced pressure. Short-duration crew reviews, such as crew station, transfer, stowage, crew compartment fit and function, etc., do not enable the crew and the crew representatives to identify all discrepancies in experiment and crew-equipment design, stowage, and usage. Mission simulation testing at altitude, using flight equipment, provided an excellent opportunity to identify and resolve discrepancies in hardware designed for flight. Many of the discrepancies identified in the Skylab medical experiments altitude test (SMEAT) might not have been discovered otherwise until during a mission. Validation of flight procedures, checklists, and nomenclature was also accomplished in the SMEAT.

BACKGROUND: The SMEAT exercised flight configuration equipment under conditions similar to those planned for flight. Several hundred anomalies were recorded and resolved long before Skylab was launched. Many corrections in nomenclature, markings, equipment handling, food and beverage quantities, waste management system urine and fecal collection equipment, and vacuum cleaner equipment resulted from the SMEAT.

S.L.L. No.: 7-6

TITLE: TEST PROCEDURES

LESSON LEARNED: Flight operational procedures should be incorporated in tests at the earliest practical/possible date.

BACKGROUND: Ground testing was the only method for verifying flight procedures for the Earth resources experiment package. When these procedures were finally tested, it was found that many of the constraints that were required to be written in were really ground test constraints not applicable to flight and were, in fact, not valid constraints at all.

S.L.L. No.: 7-7

TITLE: INTEGRATED SYSTEM QUALIFICATION TESTING

LESSON LEARNED: Integrated system qualification testing should be used instead of redundant component/subassembly testing. To determine whether the philosophy is economically desirable, a trade-off study has to be made of the increased complexity in test setup and failure isolation as opposed to the cost savings realized by the reduced number of tests.

BACKGROUND: Some Skylab medical experiment hardware had to undergo delta-qualification vibration testing when it was found that it had been tested at the subassembly level to a lower vibration level than it would encounter in its integrated system configuration.

S.L.L. No.: 7-8

TITLE: UNIFORMITY OF TEST AND CHECKOUT PROCEDURES FOR VARIOUS SITES

LESSON LEARNED: Procedures for performing identical tests at different locations should be made uniform to avoid different sequences.

BACKGROUND: Problems were encountered during testing at the NASA John F. Kennedy Space Center (KSC) because of the disparity between in-plant procedures and the KSC procedures for performance of identical tests. Frequently, the disparity was due to ground support equipment (GSE) differences; however, procedures not affected by GSE configuration should be identical for each site. Standard sequences for test preparation sheet inclusion should be provided to preclude out-of-sequence functions. Central control and dissemination of test documents is recommended.

TITLE: ACCEPTANCE TEST AND CHECKOUT REQUIREMENTS

LESSON LEARNED: Acceptance tests and checkout procedures should verify
wiring and controls separately for each path or function. Wiring
should be coded to clearly identify not only each wire in the bundle
but also the terminal at adjacent terminal boards.

Experiment hardware and subsystems should be tested in a configuration
as close as possible to the flight configuration, following functional
checkout at the vendor or integration area. Integrated systems testing
for interfacing systems, subsystems, or components should be planned
at the earliest practical phase of program planning and test require-
ments definition, and the plan should be included in the test checkout
and requirements specification document before final approval of the
document.

BACKGROUND: The service module cryogenic hydrogen tank power controls
for the fans and heaters were interchanged between tanks 1 and 2 by
miswiring at the terminal boards. The wiring for both was color coded
identically. The airlock-module/multiple-docking-adapter altitude
chamber testing at the McDonnell Douglas Astronautics Company - East
did not include a fully integrated spacecraft response to varying
extravehicular mobility unit system operations. Such integrated testing
was not accomplished until approximately 60 days before launch. If
problems had been discovered at that time, the launch schedule might
have been impacted.

SECTION 8

FLIGHT OPERATIONS

S.L.L. No.: 8-1

TITLE: IN-ORBIT CREW STAY TIME

LESSON LEARNED: Psychological and physiological conditions of the
flightcrew resulting from the 84-day visit indicated no constraints for
long-duration flights. For example, the food and sleep requirements
were about the same as on the ground; but to maintain reasonable phys-
ical condition of the muscles, 1 to 1.5 hours of deliberate daily
exercise were required by each crewman.

S.L.L. No.: 8-2

TITLE: INDIVIDUAL INTRAVEHICULAR ACTIVITY CREW TASK TIMES IN
        ZERO GRAVITY

LESSON LEARNED: As a result of one-g training experience, very few crew
tasks were found to take longer in zero gravity than had been planned.
Excessive conservatism in time lining individual tasks should be avoided
to allow more productive time in orbit; however, flexibility in time
lining should be retained to allow for general housekeeping tasks plus
routine and unscheduled maintenance.

BACKGROUND: Most Skylab individual task times were equal to or less
than one-g baselines because of the expanded "envelope of attack"
available to the crewman with respect to "getting at" the job. The
Skylab crews often asked for additional tasks to fill voids created by
conservative time lining. Exceptions to this situation were usually
associated with tasks requiring logistic management of multiple piece
parts. In the early days of each mission, housekeeping and mainte-
nance tasks often intruded into operational or experimental time blocks.

S.L.L. No.: 8-3

TITLE: EXTRAVEHICULAR ACTIVITY WORK TASKS IN ZERO GRAVITY AND
        ONE GRAVITY

LESSON LEARNED:

1. Extravehicular activity (EVA) workloads were, on the average,
    approximately 20 percent less than predicted.

2. The time required for EVA performed in one gravity (even in the
    water immersion facility) should be multiplied by 1.5 to 2.0 to de-
    termine the amount of time required to perform in zero gravity.

BACKGROUND: After 4 years of lunar-surface EVA operations with only minimal zero-g operations on the Apollo 15 to 17 missions, several unknowns still remained as to how the Skylab crewmen would perform during extended periods of zero gravity. In most instances, the crews purposely paced themselves to avoid both fatigue and errors. This was evidenced by the number of hours of EVA and the complexity and bulk of tasks performed. In most instances, ground training/simulation involved near ideal conditions with respect to lighting, assistance, hardware fidelity, etc. This system minimized crew/support personnel/facility time and optimized procedures and hardware development.

S.L.L. No.: 8-4

TITLE: PRESLEEP ACTIVITY PERIOD

LESSON LEARNED: A presleep period of 1 hour of mentally nondemanding activity should be planned in the crew's time line.

BACKGROUND: In the early phases of the missions, Skylab crewmen complained that too often they were scheduled to perform operational or experimental activities right up until the beginning of their sleep period and that it was quite difficult to relax abruptly and go to sleep. The 1 hour of uninterrupted presleep activity was observed as a constraint during Skylab 4.

S.L.L. No.: 8-5

TITLE: IMPROVE USE OF IN-ORBIT CREW TIME THROUGH GROUND CONTROL

LESSON LEARNED: Ground controlled or automatically sequenced equipment and experiments allow activities to occur during crew rest and sleep periods. Ground control should be used for repetitive or time-consuming functions that do not require onboard crew judgment. Future programs should review all functions desired during crew sleep, eat, and unmanned periods for possible accomplishment by ground controlled functions.

BACKGROUND: In Skylab, experiments such as the Apollo telescope mount (ATM) S055 and the ATM pointing control were accomplished through ground commands during unmanned periods, while the flightcrew was not in attendance. Ground control also was used successfully for the solar array electrical power generating system, the data and video recorder tape management, and the control moment gyro momentum management.

S.L.L. No.: 8-6

TITLE: PRIVATE COMMUNICATIONS

LESSON LEARNED: There was an occasional need for private communications with the crew for mission management purposes. The restrictions against such private communications in Skylab prevented a free exchange of information with the crew on the subjects of scheduling activities and workload.

BACKGROUND: Both the flightcrews and the flight control teams were reluctant to discuss flight planning and workload scheduling problems on the open air-to-ground circuit because of concern for potential misquoting or misunderstanding by the press. The capability to have some private management discussions with the flightcrew without causing concern in the press would have made resolution of some of the flight planning problems much easier. A free exchange of thinking was frequently needed to prevent potential problems of overscheduling the crew, but the Skylab rules for private communication precluded this mode of operation.

S.L.L. No.: 8-7

TITLE: STOWAGE PROCEDURES AND ONBOARD INVENTORY MANAGEMENT

LESSON LEARNED: A practical and streamlined equipment stowage inventory management and accounting system is needed during the mission operations phase of the program. The system should output crew data in the exact format to be used by the crew and should be compatible with the real-time uplink to the orbiting spacecraft for presentation on board. The system should also track other onboard data references affected by a given stowage change.

BACKGROUND: The single most difficult area of the final Skylab flight data file development for each mission was the change traffic in the stowage list document. Of necessity, the stowage list and the launch, in-flight, and return stowage locations were constantly changing. This required late and significant revisions to the stowage document, which was the crew's overall reference on loose item location, quantity, and transfers. Checklists with stowage data were also impacted.

Several instances arose in Skylab in which an item became "lost" and the ground had to institute a search through transcript review and crew questioning about last usage or sighting.

TITLE: FLEXIBLE CREW PROCEDURES

LESSON LEARNED: A flexible flight data file (FDF) that accommodates preflight and real-time changes is necessary to maximize the return from a manned space-flight mission in which the conditions change.

Future FDF's should be designed to accommodate late changes in mission requirements and changes resulting from varying conditions during the mission. Some areas to consider are:

1. Design procedures to avoid changes caused by alternate launch days.

2. Avoid highly structured detailed procedures that are unique to a single trajectory and overly sensitive to conditions that can be expected to vary.

In summary, the crew procedures system should provide the capability to change procedures, train the crewmen, and eventually uplink changes to the crew in an efficient and accurate manner without undue burden on the people who operate the system.

BACKGROUND: Many past program elements have assumed that crew procedures become static after the flight hardware is built. This assumption leads to the conclusion that crew procedures should be controlled in the same manner as the hardware configuration is controlled. Skylab, as well as previous programs, has shown that this approach is ineffective for the following reasons:

1. Training exercises continually uncover better ways of performing an operation by:

    a. Improving the procedure.

    b. Increasing the efficiency of the crew to execute the procedure.

2. Requirements are continually changing as a result of:

    a. Improvement in an investigator's understanding of his basic data requirements and the capability of his instruments to collect the data.

    b. Improvement in the capability of the operations organization to collect the required data.

c. Improvement of the understanding of the data requester's requirements by the operations organization; also, improvement of the investigator's understanding of the operational systems.

3. Conditions change (i.e., storms, earthquakes, hardware failures, etc.). The following data are indicative of the number of changes made to Skylab crew procedures:

Period of change	Skylab 2	Skylab 3	Skylab 4
Preflight	2083	677	763
Real time	86	275	413
Total	2169	952	1176

S.L.L. No.: 8-9

TITLE: REAL-TIME UPDATING REQUIREMENTS

LESSON LEARNED: The teleprinter provided greater flexibility in Skylab flight planning than had ever been possible in previous programs. A larger, more versatile teleprinter with graphics features would be highly desirable for future manned programs. Flight data file (FDF) changes should require a minimum of crew involvement; uplink entire new pages, be sure the changes fit on the checklist page format, and avoid pen-and-ink changes. If possible, uplink each crewman's messages on one continuous piece of paper. This minimizes sorting. Flight controllers should have some independent authority in communicating via teleprinter (or teleprinterlike devices). Minimize the number of interfaces required for a flight controller to transmit information to the crewmembers in orbit.

BACKGROUND: In the course of the Skylab Program, nearly 4000 teleprinter messages were uplinked, each of which varied from less than 15 to over 1000 lines in length. Information concerning every phase of mission operations items was transmitted. A significant amount of crew time was required to keep the FDF up to date.

S.L.L. No.: 8-10

TITLE: TELEPRINTER UPLINK MESSAGE GENERATION

LESSON LEARNED: Text message generation for transmission to the space-craft should be designed such that a minimum of computer and hardware interfaces is required.

BACKGROUND: In Skylab, four computers were required to generate a routine teleprinter uplink message. Computer checkpoints and unscheduled downtime frequently interrupted message generation, resulting in significant delays.

S.L.L. No.: 8-11

TITLE: SCIENTIFIC COMMUNICATIONS WITH CREW IN ORBIT

LESSON LEARNED: Frequent informal communications between the scientist astronaut in orbit and the scientific ground-support personnel significantly enhanced the amount and quality of experiment data obtained.

BACKGROUND: Data collection for the Apollo telescope mount experiments was significantly increased in quantity and quality by the frequent and rapid uplink of solar activity data generated by the National Oceanic and Atmospheric Administration by weekly (and later daily) discussions between the scientist pilot (SPT) in orbit, the Principal Investigator (PI) or his representative, and the ground-based scientist astronaut. The SPT used special uplinked data on flares and coronal and disk transients to obtain data he would have otherwise missed. His discussions with the PI's and the ground-based scientist astronaut clarified changes in procedures and program priorities and informed him of the results of current data analyses. The PI's were informed of favorable opportunities for taking data on solar phenomena of interest.

S.L.L. No.: 8-12

TITLE: ONBOARD DATA ENHANCEMENT

LESSON LEARNED: More data of better quality were obtained by allowing the onboard scientist astronaut to function as a scientist in the planning, modification, and implementation of the details of experiment operations.

BACKGROUND: In Skylab 3 and Skylab 4, substantial amounts of observation time were scheduled for the scientist pilots to permit them to

use their knowledge of solar physics and the ATM "shopping lists" to obtain unique and opportune data. During these periods, the scientist pilots functioned as scientists. The Naval Research Laboratory stated that they got their best data during observation time and that all other experiments significantly benefited from the work of the SPT's.

To obtain optimum flare, coronal, and disk transient data, it was necessary to rely on the crewman's judgment and training. The recording of early flare-rise data by the Skylab 4 science pilot required scientific judgment and perseverance, as well as a perfected operational technique and a certain amount of intuition.

During Skylab 4, it was found that many perplexing problems caused by erratic solar phenomena (disappearance of prominences, etc.) could be avoided by giving the crewmen the authority to modify the uplinked schedule and to use their judgment in selecting the best targets or alternate times to perform a given observation program.

It should be noted that the scientist pilots' enthusiasm and general morale were substantially increased by the opportunities that afforded them to function as scientists.

S.L.L. No.: 8-13

TITLE: USE OF WASTE MATERIALS EJECTED FROM A SPACE STATION OR SPACECRAFT

LESSON LEARNED: Waste gases and liquids vented from the space vehicle could be used for attitude control by venting them through directional nozzles. Even though the thrust obtained may be small, the energy could be used as the ventings occur to improve the momentum positions of the control moment gyros (CMG's) (i.e., store the energy, attained through waste dumps, for CMG's through momentum management).

BACKGROUND: Vents and dumps of gases and liquids caused unwanted momentum disturbances in Skylab. The ability to control systematically or to eliminate these momentum disturbances could have reduced the use of attitude control propellant and thus could have increased the control margin of the CMG's.

S.L.L. No.: 8-14

TITLE: DISADVANTAGES OF FRAGMENTED SKYLAB EXPERIMENT SIMULATION

LESSON LEARNED: When training in experiments operation is required during simulations, the simulation system should be designed so that the experiment simulation is integrated with the total simulation system that is comparable to the real vehicle.

BACKGROUND: The simulation system for Skylab experiments training was rather fragmented. The Skylab simulator involved only the Apollo telescope mount experiments. Most of the Saturn workshop experiments were performed in the one-g trainer that was located approximately 400 feet from the Skylab simulator. The one-g trainer output telemetry for only the biomedical experiments while other required experiment telemetry was output by the ground-systems simulation computer. The Earth resources experiment package simulator was attached to the Skylab simulator but did not interface with the Skylab simulator computer. With this type of fragmented simulation training, the crews were inconvenienced and it was difficult for simulation support personnel to keep pace with the crew's activity to ensure that all simulation systems were properly configured.

S.L.L. No.: 8-15

TITLE: JOINT OBSERVATION PROGRAM CONCEPT

LESSON LEARNED: The joint observation program (JOP) concept was excellent and resulted in the production of maximum data for minimum Principal Investigator/crew interface during the mission. The JOP's were developed before the mission for the assessment of solar features of interest. Each JOP resulted in the compilation of information regarding the solar feature, desired instrument operating modes, and pointing instructions. However, because the JOP's were developed before the mission, they could not provide for instrument malfunctions nor could they be used to exploit the knowledge gained during the mission. Consequently, future mission operations should allow for changes in the JOP's and their constituent building blocks to permit exploitation of data gathered during the mission and to compensate for instrument degradation.

TITLE: EXPERIMENT HARDWARE FAMILIARIZATION FOR MISSION CONTROL
         CENTER PERSONNEL

LESSON LEARNED: It is recommended that Mission Control Center (MCC)
console manning personnel acquire firsthand familiarization with the
operation of the experiment hardware in their respective areas of
responsibility.

BACKGROUND: The results of Skylab showed that each crewman performed
his experiment protocol differently.   These limits of variation could
be better understood and appreciated by those MCC personnel having
firsthand knowledge of equipment operation.

S.L.L. No.:   8-17

TITLE: USE OF SIMULATION CONTROLLERS AS FLIGHT CONTROLLERS

LESSON LEARNED: In future programs, consideration should be given to
using simulation controllers as flight controllers.

BACKGROUND: Most simulation controllers served as flight controllers
for Skylab.   They were given positions for which the basic required
knowledge was essentially the same as for their simulation position.
In addition, they received on-the-job training with an experienced
operator (during Skylab 2) before manning the consoles alone.   This use
of simulation controllers worked well.

S.L.L. No.:   8-18

TITLE: FUNCTIONAL SIMULATION OF COMPUTERS

LESSON LEARNED: Functional simulation of flight computers is not rec-
ommended for use in training systems.

BACKGROUND: A functional simulation of the Apollo telescope mount (ATM)
digital computer was provided in the Flight Operations Directorate sim-
ulation of the Saturn workshop.   It was not possible to maintain the
simulation in a current status with the real digital computer because
of the delay resulting from having to reprogram the system each time a
change occurred.   The functional simulation did not provide memory dump
and troubleshooting capability.   Also, when training with a functional
simulation and an unexpected response occurred, the trainee was usually
uncertain as to whether he made a mistake or the simulation was working
incorrectly.

The Skylab simulator had a real ATM digital computer, which could be updated by playing in a tape of the latest flight program. It was an excellent training tool and provided easy, rapid, and inexpensive update capability.

S.L.L. No.: 8-19

TITLE: REAL-TIME MISSION PLANNING REQUIREMENTS

LESSON LEARNED: A formal communication system between science planning personnel and console operators is required to ensure continuity in planning, execution, and analysis of science programs. Some suggestions for accomplishing such a system are as follows:

1. Hold the planning conference in a room adjacent to the science room so that the execute "czar" (ATM principal spokesman) can attend. This would also allow the "execute plans" personnel to answer questions and would eliminate the need for flight control personnel to support the conference full time.

2. Use two execute czars with one in the science room and one serving as planning chairman. They would exchange duties each day; this would allow the czar to execute the plan he developed the previous day at the planning conference.

3. Require each instrument group to provide detailed written rationales for their planned experiment modes each day.

BACKGROUND: During Skylab, the execute czar did not always understand the plans developed by the planning conference. In one instance, he thought some plans were in error and therefore changed some instrument operating modes and pointing to the consternation of the Principal Investigator, who had deliberately planned the modes. In other instances, the execute czar could not answer crew questions regarding the plan and did not have a strong basis for making real-time inputs. Conversely, information gathered by the console czar was often not passed along to the planning conference, and the summary czar had very little input from the conference regarding the summary plan inputs he should make.

S.L.L. No.: 8-20

TITLE: LOW-PRIORITY EXPERIMENTS FOR FLEXIBLE FLIGHT PLANNING

LESSON LEARNED: It was extremely useful to the flight planners to have several low priority experiments available that did not have firm

scheduling requirements. These experiments were used as "fillers" when time was available between the "regular" experiments.

BACKGROUND: In designing the daily flight plan during Skylab, it was not always possible, for a variety of reasons, to fill the time available with the preplanned experiments. In such cases, it was useful to have a reservoir of activities, which could be used to fill this open time. Ideally, such activities should be reasonably short, one-man tasks that are not critical. On Skylab, such tasks included a series of science demonstrations, low-priority experiments and detailed test objectives that had been approved before the mission on an if-time-is-available basis, and non-time-critical experiment or systems test activities generated during the mission. Scheduling of these activities contributed to increased efficiency in the use of crew time by providing worthwhile activities in an otherwise idle time period.

S.L.L. No.: 8-21

TITLE: AVAILABILITY OF PRINCIPAL INVESTIGATORS DURING MISSION OPERATIONS

LESSON LEARNED: Except for the most routine and passive experiments, it is extremely useful for the Principal Investigator (PI), or someone who can speak authoritatively for a given experiment, to be physically available during the mission.

BACKGROUND: During Skylab, there were many occasions during both experiment operations and planning meetings when questions arose that could only be satisfactorily answered by an authoritative spokesman for the investigator. To provide realistic inputs to the scheduling of experiment activities during the mission, the experimenter must maintain an up-to-date knowledge of the mission situation including the overall constraints and limitations that influence his experiment accomplishments. The best way to maintain such knowledge and to ensure the inclusions of such inputs was for the PI to be on the scene continually during the mission. When the spokesmen were available in the experiment support rooms or at the planning meetings, their inputs were timely and effective. On occasions when the PI's were not available, use of the long distance telephone was often ineffective and resulted in some reduced efficiency in performing the experiment. The difficulties with the use of the telephone were attributed to the following problems:

1. Difficulty in locating the individual needed on short notice, particularly because some of the questions came up at unpredictable times.

2. Inefficiency of the telephone as a means of communicating complex situations to the absent PI, as well as the need to bring him up to date in most cases.

S.L.L. No.: 8-22

TITLE: IMPROVE PRINCIPAL INVESTIGATOR DATA VIEWING FACILITIES

LESSON LEARNED: For future missions, suitable locations should be provided for principal investigators to review flight data. These facilities should be equipped to display science data for quick turnaround.

BACKGROUND: Principal investigator quick turnaround data reviews were often delayed several hours because the reviewer had to locate a spare corner, a room, or an office in which to review the data. Display facility suggestions are as follows:

1. There should be sufficient space between data-viewing devices for several reviewers to assess the data simultaneously.

2. Tables should be provided adjacent to each display device for note taking and hardcopy review.

3. The data reviewing room should be large enough to support multiple disciplines simultaneously. This suggests that a minimum number of each type of display device should be made available.

4. The facility should not necessarily be located in the Mission Control Center; however, it should be closely located and should contain appropriate communications equipment to allow rapid feedback to mission operations.

S.L.L. No.: 8-23

TITLE: MISSION OPERATIONS CONTROL ROOM POSITIONS FOR MAJOR EXPERI-
        MENT AREAS

LESSON LEARNED: The creation of mission operations control room (MOCR) positions representing the major experiment areas was an effective technique for handling the operational aspects of the Skylab experiments and also for providing daily inputs to the experiments flight planning.

BACKGROUND: During Skylab, there were Apollo telescope mount, Earth resources experiment package, medical, and corollary experiment flight controllers who had a thorough understanding of the requirements, hardware constraints, and operational limitations of their experiment areas

and who contributed significantly to the successful operation of their experiments. These experiment flight controllers manned positions in the MOCR, on a three-shift basis, as regular members of the flight control teams with ready access to the flight director.

S.L.L. No.: 8-24

TITLE: PROGRAM SCIENTIST

LESSON LEARNED: The Skylab Program Scientist provided an effective interface between the experiment investigators and the flight control team for establishing daily experiment schedules and for resolving conflicts among scientific disciplines. The Program Scientist, serving as a single point of contact, represented the Program Manager in dealing with the scientific investigators, and he represented the scientific investigators in dealing with the Flight Director.

The Program Scientist found it advantageous to hold science planning meetings twice weekly with the scientific investigators to mutually work out the scientific experiment priorities and scheduling guidelines for the next 7 days.

BACKGROUND: During the premission simulations, it was found that resolution of scientific tradeoffs and issues required the full-time attention of one individual representing the program management. Scientific expertise and experience were needed to resolve the numerous issues intelligently. Designation of a Program Scientist, who would report to the Program Manager and work daily with the investigators and the flight control team, solved this problem.

The Program Scientist found that having all the scientific investigators represented at biweekly science planning meetings had two substantial advantages:

1. Scientific tradeoffs among experiments could be resolved much more readily when all parties to a tradeoff or conflict could discuss the possible solutions face to face. In almost all cases, agreements could be negotiated when all facets of the issues were mutually understood.

2. By resolving priority conflicts in an open forum, all investigators could see that their experiments were receiving equitable consideration.

C.2

S.L.L. No.: 8-25

TITLE: FLIGHT MANAGEMENT TEAM MEETINGS

LESSON LEARNED: Daily meetings of the flight management team during
the manned Skylab missions were an effective method of ensuring that
the conduct of the mission conformed to program requirements. Revisions
of scientific priorities, approval for scientific test objectives that
infringed on normal operational guidelines, approval of added scientif-
ic activities, and other changes in mission requirements were handled
by the flight management team.

BACKGROUND: The Mission Requirements Document for each mission defined
the intended content of each Skylab mission. Because of unexpected
developments, innumerable changes, variations, and interpretations of
the mission requirements were necessary on a day-to-day basis. For
example, unique lighting conditions made it desirable to get the crew
up 2 hours early for a special Earth resources observation. In another
case, simultaneous observations with Pioneer satellites were desired;
this development required a temporary change in experiment priorities.
Decisions on numerous issues required senior program management approval.
This activity was accomplished readily through the flight management
team meetings chaired by the Program Director (or his deputy).

S.L.L. No.: 8-26

TITLE: FIXED FORMAT VARIABLE DATA DISPLAYS FOR MISSION OPERATIONS
        COMPUTER

LESSON LEARNED: Consideration should be given to the design and use of
fixed format variable data displays as opposed to the rigidity/formatted
displays in the mission operations computer (MOC). Also, once a dis-
play has been reconfigured or changed, it should remain in the changed
configuration.

BACKGROUND: The MOC tabular displays used in support of Skylab (e.g.,
universal digital display 1919) were very useful. In fact, they were
used for the entire mission when the capability to change displays was
absent. Extension of this idea to include summary tabulations should
be considered. Because of the rapid turnaround and variable missions
being planned for the future, the long lead time required to change the
rigidity formatted displays will prohibit their use. Designing the
display system to allow real-time reconfiguration should eliminate this
problem.

S.L.L. No.: 8-27

TITLE: MISSION OPERATIONS COMPUTER LIMITS DISPLAY

LESSON LEARNED: Limits should be included with the associated teleme-
try parameters in tabulated mission operations computer (MOC) displays,
even at the expense of losing several columns of history data.

BACKGROUND: On Skylab, limits were displayed on separate formats from
the systems data displays. This made it necessary to cross reference
parameters and limits from the two displays, which became very time
consuming and led to many human errors.

S.L.L. No.: 8-28

TITLE: TELEMETRY DATA STORAGE AND RETRIEVAL FACILITIES

LESSON LEARNED: Better telemetry data storage retrieval facilities
are required to aid systems problem solving and experiment data evalu-
ation support.

BACKGROUND: The master data base (DB) technique that evolved in Skylab
would be unacceptable for future programs. It was very easy to store
real-time data in one DB and the corresponding non-real-time data in a
second DB. However, problems were created in generating trend infor-
mation. Serious consideration should be given to providing the follow-
ing capabilities:

1. One continuously accessible master DB containing all data for a
    particular mission (this implies some method of data compression
    and a large storage capability).

2. If continuously accessible data storage is not feasible, a single
    DB with a 10-day storage capacity and a selective purge capability
    (as opposed to the complete purge as in Skylab) should be provided.
    In general, this type of data storage system lends itself to solv-
    ing systems problems and evaluating experiments data that require
    data covering long periods of time. This type information was dif-
    ficult to obtain in Skylab because of the limited size of the DB's
    and the very small capability to load the history data.

3. Storing data in archives must be done so that individual vehicles
    can be loaded from archives in the history DB. Data should either
    be archived by vehicle, or a system capability should exist to load

data into the history DB from archive by vehicle to make history loading faster and to provide more DB availability for the vehicle of interest.

4. The data storage and retrieval facility should perform functions such as tape generation, purge/load, archive function, and terminal input requests in a time-shared manner and not in an exclusive sequential fashion. In Skylab, one archive function significantly decreased response time for terminal inputs and inhibited such functions as load/purge and tape generation.

5. Indexing archives should be added to the software so that searches can be made.

S.L.L. No.: 8-29

TITLE: ANCILLARY COMPUTER SUPPORT FOR MISSION CONTROL CENTER CONSOLE OPERATION

LESSON LEARNED: A small digital computer with programing capability (e.g., commercial desk type) can be used as an effective supplement to the ground processors. This small computer can be programed quickly to fill "gaps" created by new mission objectives that inevitably arise as the mission progresses.

BACKGROUND: This capability was used frequently during the Skylab Program.

S.L.L. No.: 8-30

TITLE: OFF-LINE DATA PROCESSING FOR SPACE EXPERIMENTS

LESSON LEARNED: It is recommended that an off-line data processing system, such as the telemetry history reports in formatted tabulation (THRIFT) system used for the Apollo Program, be instituted or that spacecraft experiment data are provided directly to the user for processing.

BACKGROUND: A THRIFT-type system would minimize routine terminal operations and unload the Mission Operations Planning System (MOPS) machines. A significant amount of MOPS terminal time was devoted to generating experiment data reports, which prohibited the machines and terminal from being used to assess systems status. Experiment data processing could have been handled off line or at a remote user location. This approach would also have freed the systems engineers to monitor the systems more closely.

S.L.L. No.: 8-31

TITLE: USE OF STORED COMMAND SEQUENCES

LESSON LEARNED: Stored program command loads should be developed for
repetitive and fast reaction unattended programs such as synoptic and
flare joint observation programs for the Apollo telescope mount (ATM).
Onboard sequences as well as ground sequences should be considered.

BACKGROUND: The ATM synoptic program was normally performed on a reg-
ular basis and rarely changed. Unattended flare and transient programs
required immediate reaction and were automatic. Joint observation
programs could be programed so that they could be activated by only one
command. This would have permitted activating the programs at Space-
flight Tracking and Data Network sites with acquisition of signal times
less than the required 8 minutes.

S.L.L. No.: 8-32

TITLE: GROUND COMMAND SYSTEM REDUNDANCY

LESSON LEARNED: Avoid building complex command execution redundancy
into a ground system designed to support manned spacecraft. Any com-
mands too critical to be delayed for ground system problems should be
capable of onboard execution with proper voice instruction.

BACKGROUND: For Apollo and Skylab, a "Mode 1" remote site backup com-
mand execution capability was established to protect against data line
loss between the Mission Control Center (MCC) and remote sites. This
capability was seldom used, because the ground system problem was usually
caused by a loss of the command computer at the remote site rather than
malfunctioning data lines. Also, it was highly impractical if more
than one MCC console required "Mode 1" execution at a single site.

SECTION 9

MANAGEMENT

S.L.L. No.: 9-1

TITLE: CREW RESCUE PROCEDURES TRAINING

LESSON LEARNED: The NASA should periodically either train rescue elements directly or oversee the training conducted by the Department of Defense (DOD).

BACKGROUND: Cognizant NASA personnel are usually more familiar with the operational procedures for space crew rescue and more experienced in operating the associated equipment, primarily because of their involvement in developing the equipment and procedures. Also, in Skylab there was a greater continuity in NASA personnel assignments as opposed to the frequent turnover of DOD personnel. Additionally, NASA personnel were involved with the equipment and procedures and were cognizant of the latest changes.

S.L.L. No.: 9-2

TITLE: PROCEDURAL DECALS AND LOOSE INSTRUCTION SHEETS

LESSON LEARNED: Procedural decals and loose instruction sheets are an integral part of crew procedures and, as such, should be distributed to those principal recipients of the flight data file (FDF). They should be subject to change and updates in the same manner as those related procedures in the FDF. They should not be stowed with the hardware as loose instruction sheets but rather as cue cards.

BACKGROUND: Procedural decals and loose instruction sheets caused procedural problems for the following reasons:

1. Decals were not distributed to the same distribution lists as FDF items and, therefore, did not receive the same level of review as FDF items.

2. Large engineering drawings were often used to document decals, thereby making it difficult to locate a decal of interest.

3. Decals could be generated and installed without significant visibility from the total operations team.

4. Once launched, decals could be changed only by launching a new decal on a subsequent flight even though related procedures may have been modified.

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S.L.L. No.: 9-3

TITLE: EXTRA IN-ORBIT EXPERIMENT CONSUMABLES

LESSON LEARNED: Carrying more experiment consumables (film, tapes, etc.) than had been included in the planning requirement before the mission and providing in-flight spares for experiments were found desirable to the extent permitted by stowage and weight limitations.

BACKGROUND: The extra experiment consumables permitted increasing the time allocated for experiments to take advantage of situations in which:

1. More time became available for all experiments than had been anticipated.

2. More time became available for some experiments because of the failure of other experiments.

3. The emphasis on a given experiment was increased because of unanticipated scientific phenomena (e.g., more active Sun).

The availability of in-flight spares to repair a failed experiment is an obvious advantage and need not be limited to sparing the entire instrument. On both Skylab 3 and Skylab 4, the spare film cannister on SO19 permitted the continuation of this experiment after one cannister had jammed. Other examples during Skylab included the use of more Earth resources experiment package tapes and SO82 film than planned for the second mission and then replacing these consumables on the subsequent launch.

S.L.L. No.: 9-4

TITLE: LOW-PRIORITY EXPERIMENT REQUIREMENTS

LESSON LEARNED: The acceptance of firm requirements for the performance of low-priority experiments during the very early portion of a mission (first week) should be avoided on missions that require substantial amounts of activation.

BACKGROUND: During each Skylab mission, the first week was extremely busy and time was at a premium. Requirements for early observations for low-priority experiments resulted either in undue interference with the performance of high-priority experiments or failure to meet the requirements of the low-priority experiments.

S.L.L. No.: 9-5

TITLE: OPERATIONAL SUPPORT TO EXPERIMENT GROUPS

LESSON LEARNED: Establish early contacts and information exchange
between experiment developers and crew operations specialists. An
operations representative knowledgeable about crew requirements and
capabilities should be designated to work with potential experiment
suppliers as soon as an experiment is seriously considered for assign-
ment to a manned space-flight system. Experiment developers should be
encouraged to learn what can and cannot be done by space crews before
they proceed with hardware design.

BACKGROUND: The basic operational design, the tentative crew proce-
dures, and the compatibility with mission operations of several Skylab
experiments definitely suffered from a lack of crew operations inputs
early in the development cycle. The resulting need for hardware
redesign, procedural workarounds, and/or continual procedures and time-
line changes proved frustrating to the experimenter and crews and
posed a significant problem to procedures and flight-planning
specialists.

S.L.L. No.: 9-6

TITLE: REQUIREMENTS DOCUMENTS APPLICATIONS

LESSON LEARNED: Environmental requirements for Government furnished
equipment (GFE) hardware should be tailored to the function, criti-
cality, and complexity of the hardware. The broad application of
generalized requirements and general environmental specifications
to the different types of hardware can result in design impact to
accommodate a specification condition that may not apply to the system
under design. Excessive documentation effort and costs can be avoided
by appropriate tailoring of requirements early in the program.

BACKGROUND: In the early part of the Skylab Program, the environmental
requirements for GFE and experiments were obtained from the Apollo
Applications Program (AAP) cluster requirements specification. The
vibration levels were presented in very broad terms for gross areas
of the cluster. Because these levels were severe, they were scrutinized
very carefully. Much less severe levels were found to actually exist
for the particular locations for many hardware items. The extra-
vehicular activity thermal environment was not included as part of the
cluster requirement specification, and a special set of conditions
peculiar to the operating requirements of the extravehicular equipment
had to be generated. A special document, CSD-S-033, "Design Environments

for CSD Provided Hardware," was generated from the cluster requirements specification, other engineering sources, and analyses. This document tailored the general requirements to the specific class of hardware furnished by the NASA Lyndon B. Johnson Space Center.

S.L.L. No.: 9-7

TITLE: GOVERNMENT FURNISHED EQUIPMENT DATA DISSEMINATION

LESSON LEARNED: Transmittals of Government furnished equipment (GFE) data such as drawings, specifications, interface control documents, preinstallation acceptance documents, and stowage installation drawings were disseminated through a single office assigned the responsibility for ensuring the validity, accuracy, and timely transmittal of the data.

BACKGROUND: With some 300 items of ancillary GFE and 18 data requirements for each item, informal data transmittals caused severe accountability problems. Different sites had different data on the same GFE items. Verbal requests among Centers, contractors, and technical monitors increased. To solve these problems, a data requirements checklist was prepared for each item, and all transmittals of data were recorded. All transmittals were made by a single office, and the checklists accompanied the transmittals. Redundant transmissions ceased and omissions were corrected. Uniformity in the data resulted, and the previous communication problems were eliminated.

S.L.L. No.: 9-8

TITLE: COMPLETE CHANGE PACKAGE CONCEPT

LESSON LEARNED: An attempt to establish a complete hardware change package concept tended to cause more problems than it solved. The rule of not processing a change until all related documentation changes were included in the package delayed the processing of important changes. A backlog of changes should not be allowed. Potential changes should be brought before a configuration control board (CCB) on a timely basis for initial approval or disapproval, without waiting to complete all the related documentation changes.

BACKGROUND: During the early phases of the Skylab Program, many configuration changes were approved; however, as implementation proceeded, related changes were identified in other documentation and processed separately. To correct the situation, the total change concept was put into effect in 1971.

This concept had many shortcomings. For example, a proposed change could not be brought to the CCB until the mission requirements document and stowage list change paper were prepared. This process was very slow because of the low priority for changes that did not have CCB approval. In late 1972, there was a backlog of more than 60 major changes for which complete change package requirements were not fully met. The solution was to hold several inter-Center CCB meetings on all outstanding changes with the best available data being presented to the board at that time. The CCB minutes provided authority to proceed or stop work on each questionable item.

S.L.L. No.: 9-9

TITLE: CONSOLIDATED STATUS OF GOVERNMENT FURNISHED EQUIPMENT REQUIREMENTS AND DELIVERIES

LESSON LEARNED: A consolidated report was prepared and maintained on the quantity and schedules for all Government furnished equipment (GFE) required to support spacecraft testing and launch. This report served as a single authoritative source of information to the hardware suppliers and to the receiving organizations. Information on each item of GFE required to support each spacecraft test procedure should be developed early in the program and updated regularly. Data that record planned and actual deliveries to satisfy the spacecraft test requirements should also be maintained.

BACKGROUND: Early in Skylab, many status reports were issued for various GFE and experiment items, but there was no single source of data that indicated each equipment item required for each test sequence at each site. Matrices were devised that indicated all these requirements. The matrices provided the basis for the development of control sheets that indicated delivery status for each requirement.

As a result of this activity, reliable status information was available, and the visibility necessary for effective GFE management resulted. The GFE deliveries for test and checkout activities at McDonnell Douglas Astronautics Company - West, McDonnell Douglas Astronautics Company - East, the George C. Marshall Space Flight Center, Martin Marietta Corporation, and the John F. Kennedy Space Center were accomplished on a timely basis for essentially all test requirements.

S.L.L. No.: 9-10

TITLE: USE OF SPECIFICATION/ASSEMBLY DRAWINGS FOR SIMPLE HARDWARE END-ITEMS

LESSON LEARNED: Certain types of hardware lend themselves to a simpler method than an end-item specification for detailing the design and performance requirements and assembly, while still providing for adequate definition, control, qualification, and delivery of flight items. A specification/assembly drawing that shows the pictorial requirements together with design, performance, qualification, and acceptance test requirements was found to be adequate for numerous simple items of Skylab hardware.

BACKGROUND: Although NASA Procurement Circular (NPC) 500-1 is appropriate for complex items incorporating many lesser items requiring new design, it imposes requirements far in excess of those needed for nonfunctional items or items requiring use of off-the-shelf hardware with minor modifications. A specification/assembly drawing was used during Skylab to meet the rapid response necessary to provide a flight article within constrained time lines. This method proved satisfactory, resulted in meeting the mission schedule at a great cost savings (estimated at a factor of 10 to 1), and satisfied the requirements of safety, reliability, quality, and configuration control.

A comparison of NPC 500-1 requirements (unmodified) as shown in MSC 01480, 01481, 01360, 01399, 01400, 01402, 01482 and 01485 (specifications for comfort clothing) and SEC 11100124 (specification/assembly drawing for orbital workshop firehose) provides a graphic example of the amount of reduction in data in the use of the different methods.

S.L.L. No.: 9-11

TITLE: COORDINATION WITH SCIENTISTS AND PRINCIPAL INVESTIGATORS

LESSON LEARNED: For short-duration missions, the following guidelines are recommended to maximize the scientific results:

1. A definitive scientific management program should be developed within NASA, and each Principal Investigator (PI) should be informed of his responsibilities to NASA as well as NASA's responsibility to the (PI).

2. The grouping of similar experiments into a single package (such as Apollo telescope mount (ATM)) is highly desirable from a scientific and economic standpoint.

3. The ATM czar (the ATM principal spokesman) concept should be expanded with the czar at mission control empowered to make decisions and conduct detailed planning within broad guidelines provided by the PI's.

4. Real-time data downlinks must be used to provide quick-look results that can be exploited during the mission. If telemetry data are provided, the PI's must be able to use it and the flight control system must be flexible enough to accept real-time procedure changes resulting from the quick analysis of the data.

BACKGROUND: Coordination among PI's within a given science discipline was sometimes difficult, even though all were located at the NASA Lyndon B. Johnson Space Center. Use of the czar concept provided good coordination among the ATM PI's.

S.L.L. No.: 9-12

TITLE: THE NASA/DEPARTMENT OF DEFENSE OPERATIONAL SUPPORT INTERFACE

LESSON LEARNED: The NASA Lyndon B. Johnson Space Center (JSC) should maintain single points of contact with the Department of Defense (DOD) for the various types of military support required. The DOD point-of-contact organization(s) should be co-located with their NASA counterparts for any real-time operation.

BACKGROUND: During the Skylab and earlier programs, this single point-of-contact relationship was maintained for recovery support, including postretrieval logistics and NASA recovery communications, through the DOD Manned Space Flight Support Office (DDMS). This single point-of-contact relationship provided the following advantages:

1. More effective and continuous communications while not precluding direct interface between JSC representatives and individual DOD elements.

2. Direct interface with a DOD organization having the authority to take immediate action in directing its subordinate elements resulted in more effective and timely support to JSC's requests.

3. Only one financial contract was necessary.

4. A DOD point of contact was able to determine which DOD organization could best provide the requested support.

5. The DOD point of contact was able to eliminate unnecessary requests from other DOD elements.

The NASA recovery/DDMS interrelationship during Project Mercury, and the Gemini, Apollo, and Skylab Programs worked satisfactorily, even though DDMS was located at Patrick Air Force Base, Florida, and NASA recovery was located at JSC, only because DDMS personnel relocated themselves to JSC during actual operations. During simulation exercise, it was not possible to control the operation adequately when this co-location did not exist.

S.L.L. No.: 9-13

TITLE: AUTOMATIC DIGITAL NETWORK TELETYPE SUPPORT

LESSON LEARNED: The Department of Defense (DOD) Automatic Digital Network (AUTODIN) system is an effective system for transmittal of operational teletype traffic to military elements.

BACKGROUND: Recovery teletype support for the latter Apollo missions and the Skylab Program was provided almost entirely through the DOD common user system, AUTODIN, instead of through dedicated circuitry. This system is considerably less costly than dedicated circuitry or commercial carriers; instead of paying monthly rates (for dedicated circuitry) or instead of paying on a "per work" basis (for commercial carrier), NASA pays only for access to the system. Also, an adequate "transmittal to receipt" time line can be provided through the AUTODIN system for operational traffic if a "priority" or "ops immediate" precedence is used.

S.L.L. No.: 9-14

TITLE: LEASING DEPARTMENT OF DEFENSE VOICE CIRCUITRY

LESSON LEARNED: When possible, the NASA should lease voice circuitry through the Department of Defense (DOD).

BACKGROUND: During Skylab and earlier missions, NASA leased recovery-related circuitry through the Defense Communications Agency (DCA). When a joint NASA/DOD effort is involved, it is possible for NASA to obtain circuitry through the DOD at minimum cost. In some instances, this savings is as much as 50 percent when compared with the cost of leasing the circuitry directly from a commercial carrier. This savings is possible because the DCA, through its suborganization, the Defense Commercial Communications Office (DECCO), leases groups of circuits (called "telpak") between many locations. Additionally, if the primary use of the circuit is for DOD purposes and the circuit is already available from DCA assets, the DOD may provide the circuit at no cost

to NASA. It should be noted that in the past, the DOD could not provide circuitry to NASA unless the application of the circuit was DOD related.

S.L.L. No.: 9-15

TITLE: EXPERIMENT DATA HANDLING PROCEDURES

LESSON LEARNED:

1. Establish single control authority for the complete experiment data processing to ensure maximum commonality, including the review, analyses, and resolution of experiment data processing problems and interfaces.

2. Assign experiment data decompression processing to a single organization.

3. Use only one computer system in each data processing operation in which various manufacturer's tape drivers are used.

BACKGROUND: Three coordination organizations were involved in Earth resources experiment package (EREP) data processing. The EREP downlink data tapes were processed through three laboratories to obtain computer compatible tapes. For example, biomedical tapes were prepared by the 1110 UNIVAC for the Xerox computer; EREP decompression computer compatible tapes were prepared on Ampex and Control Data Corporation drives at one location; they were prepared for UNIVAC drives at a second location, and for IBM/UNIVAC drives at still a third location. Each time computer compatible tapes were prepared on one manufacturer's drive for processing on another manufacturer's equipment, a compatibility procedure had to be established and managed on a continuous basis. The greater the number of organizational elements involved, the more complex and time consuming the problems.

S.L.L. No.: 9-16

TITLE: PUBLIC AFFAIRS OFFICE PARTICIPATION

LESSON LEARNED: Public Affairs Office (PAO) participation in mission monitoring and in-flight management team meetings facilitated effective dissemination of accurate news information. The PAO sponsored a press briefing by the Flight Director during each shift change to keep the press up to date on mission progress and developments.

BACKGROUND: The PAO participation in mission support and mission management activites was mandatory to ensure that released information was accurate. Periodic press conferences with the crew in orbit were found to be satisfactory if some prior screening of the questions had been accomplished.

S.L.L. No.: 9-17

TITLE: COORDINATE SYSTEMS - MASS PROPERTIES

LESSON LEARNED: A minimum number of coordinate systems should be adopted to avoid the confusion and the number of coordination meetings resulting from multiple coordinate systems.

BACKGROUND: The Apollo and Skylab Programs used numerous different coordinate systems. The Skylab Program used 10 distinct systems. Much confusion and coordination activity resulted from the efforts to transfer from one coordinate system to another.

SECTION 10

QUALITY ASSURANCE

S.L.L. No.: 10-1

TITLE: GOVERNMENT SOURCE INSPECTION ON DEVELOPMENT VERIFICATION TEST
UNIT HARDWARE

LESSON LEARNED: The requirement for Government source inspection of
development verification test unit (DVTU) hardware, with its associated
problems of implementation, is not justified in view of the intended
usage of the hardware.

BACKGROUND: On several Skylab experiments (e.g., MO92 and Ml33),
problems were encountered at the time of delivery of DVTU hardware for
which source inspection was required. The inspector was at a disadvan-
tage because he did not have a NASA governing specification to follow
(the end-item specification was not applicable to DVTU hardware), and
considerable confusion and some delay resulted. In addition, minor
performance discrepancies that were acceptable to the NASA Lyndon B.
Johnson Space Center technical monitor proved to be difficult to
resolve with the government source inspector, and some delays in
delivery occurred.

S.L.L. No.: 10-2

TITLE: ACCEPTANCE DATA PACKAGE REQUIREMENTS

LESSON LEARNED: Skylab data packages contained information that could
have been delivered to the NASA Lyndon B. Johnson Space Center (JSC) in
a more efficient manner. Some examples of this information are
engineering drawings; operating, maintenance, and handling procedures;
configuration specifications; acceptance review reports; and all
material review records.

A program-wide document defining the necessary contents of the accept-
ance data package (ADP) should be prepared early in the program, and
its requirements should be binding on all contractors and other
cognizant Centers.

BACKGROUND: Acceptance data packages were delivered to JSC for file:
one remained with the contractor, and one copy was sent with the
hardware. This resulted in all data requiring revision to be period-
ically updated, even ADP's that were not being used. In the future,
any data not specifically required for receiving inspection should be
excluded from the ADP. Hardware for Skylab was being delivered from
various contractors and Centers with no uniformly established ground
rules regarding deliverable data elements for the ADP. The George C.
Marshall Space Flight Center issued MPD 8040.14 and JSC established its

requirements by letter KT-72671. Both documents were released after hardware was moving through the delivery cycle, and total compliance was not possible.

REFERENCE: JSC-KA-68-1, MPD 8040.14, JSC ltr KT-72671, and MSFC ltr SL-AL/MDA 332-72.

S.L.L. No.: 10-3

TITLE: USE OF CONTRACTOR PERSONNEL IN LIEU OF NASA INSPECTORS TO VERIFY PRODUCTION

LESSON LEARNED: The use of contractor manufacturing personnel in lieu of a NASA inspector to verify production sequences may improve timing and reduce costs.

BACKGROUND: During the Skylab Program, verification of planning sequences by contractor personnel was instituted. Selected lead men were trained and authorized to validate inspection sequences with a "Manufacturing Verify" stamp. Inspection time and cost were reduced by this in-line method of verification. Because of the success of the endeavor, certain selected manufacturing personnel below the lead man level were also trained and authorized to function in the "Manufacturing Verify" practice. The system should be considered and expanded for future programs.

S.L.L. No.: 10-4

TITLE: PROTECTION OF CRITICAL EQUIPMENT DURING STORAGE AND TRANSPORTATION

LESSON LEARNED: Equipment in short supply, easily susceptible to shock or water damage, or not easily replaceable should be protected in storage warehouses and transportation vehicles as follows:

1. Place duplicate equipment at different locations as a means of protection from adverse environments.

2. Transport flight and backup articles by separate shipments.

3. Shelter equipment from rising water or leaky roofs that can result from storm damage.

4. Store shock-susceptible equipment on lower shelves to minimize the potential energy in case the equipment should fall or be dropped.

5. Place rails on all shelves where critical equipment is located and fasten shelves to surrounding building structure to avoid equipment damage during earthquakes, Earth tremors, or other means of shaking shelves.

6. Consider special handling for critical equipment to reduce the risk of damage.

BACKGROUND: A series of Earth tremors during 1972 and 1973 in diverse places increased the concern for protection of equipment vital for Apollo, Skylab, and Apollo-Soyuz Test Project (ASTP) space operations. Cans about the size of Apollo gyros were thrown from foodstore shelves in Ventura, California, by an Earth tremor. An Earth tremor also rocked Boston. Both of these locations had Apollo, Skylab, and ASTP guidance and navigation equipment housed near the epicenter. Preventive action was applied immediately, and incremental audits were carried out for verification. In another incident, one major Skylab experiment was involved in a truck accident.

SECTION 11

SAFETY

S.L.L. No.: 11-1

TITLE: EXPERIMENT WINDOWS IN SCIENTIFIC AIRLOCKS BECAME STRUCTURAL
ELEMENTS

LESSON LEARNED: Windows and structures in simple scientific experiments
became parts of the basic Skylab pressure vessel when they were installed
in the scientific airlock. Additional rigor and analysis were required
for these experiments, particularly with regard to the glass windows,
because failure could cause loss of pressure in the orbital workshop.

BACKGROUND: The importance of some of the experiment windows exposed
to vacuum was recognized following a detailed scrutiny and assessment
of all Skylab windows. Small experiment suppliers were not prepared to
perform the detailed fracture mechanics analysis on their windows com-
mensurate with crew safety. Accordingly, to ensure the safety of the
design, both the NASA Lyndon B. Johnson Space Center and the NASA
George C. Marshall Space Flight Center performed such analyses and
established the necessary design requirements that were subsequently
implemented.

S.L.L. No.: 11-2

TITLE: CONTRACTOR SAFETY TASKS

LESSON LEARNED: Contractor safety tasks should be defined and bounded
in the statement of work. Tasks should be tailored to the hardware to
be developed.

BACKGROUND: Implementation of a safety program after the contract has
been awarded is difficult and expensive. Early implementation of the
safety program will ensure that safety requirements are included in the
hardware design without costly changes.

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SECTION 12

PROGRAM CONTROL

TITLE: STOWAGE NOMENCLATURE STANDARDIZATION

LESSON LEARNED: Hardware nomenclature should be standardized through-
out a program. On Skylab, many names existed for a single item, and
this nonstandardization resulted in confusion, ambiguity, and lost time
during communications among various user groups.

BACKGROUND: On Skylab, the nomenclature of a given item varied
relative to drawings, stowage lists, flightcrew titles, nameplates and
decals, and weight reports.

SECTION 13

EXPERIMENTS

S.L.L. No.: 13-1

TITLE: EXPERIMENTS GUIDELINE DOCUMENT

LESSON LEARNED: A simplified NASA document should be prepared and issued for use by the manned space-flight experiment developers. The document should be an accurate and easy-to-understand guide that can be used by organizations with little or no previous experience with NASA programs.

BACKGROUND: The Apollo Applications Program Experiments General Specification Document, which was prepared by NASA Headquarters in March 1969, was an attempt to provide the Skylab experiment developers with such guidelines. It coordinated the rigorous NASA Lyndon B. Johnson Space Center Apollo Applications Program Experiment Hardware General Requirements with other Centers and provided instructions on the importance of extracting minimum applicable requirements. However, it became increasingly evident during various phases of the program that some universities, hospitals, small laboratories, and large corporations acting as experiment developers were nevertheless unaware of many of the necessary NASA regulations, procedures, and requirements. In addition, some experiment developers, although aware of many of the necessary NASA requirements, had no idea of how to go about the task of satisfying them; other experimenters chose to ignore the various requirements because of contractual interpretations. The previously mentioned situations have proved costly and could be minimized if a document were prepared for small and first-time NASA contractors that would assemble the critical requirements (both technical and managerial) into a logical, unambiguous sequence with specific references.

S.L.L. No.: 13-2

TITLE: EXPERIMENT REQUIREMENTS DOCUMENTS

LESSON LEARNED: Experiment requirements documents (ERD's) should clearly define what the experiment investigator requires and the results he expects. The ERD's should not include detailed implementation data because the latter requirements are subject to frequent change and are necessarily documented elsewhere.

BACKGROUND: Skylab ERD's, especially on medical experiments, included many details from the end-item specifications, the installed and stowed crew procedures, test procedures, etc. Inclusion of these details caused a very high traffic in documentation changes to the ERD's on a monthly basis without significant benefit.

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S.L.L. No.: 13-3

TITLE: EXPERIMENT RETURN REQUIREMENTS

LESSON LEARNED: Requirements that impose constraints on the return of
experiments must be submitted early enough before a mission to allow
time for adequate review and preparation for implementation.

BACKGROUND: Requirements imposing constraints on the return of Skylab
experiments were often submitted so late that they were difficult, if
not impossible, to meet. These requirements were often incompatible
with the operational capability of the return containers or the ship-
board removal environment, and their late submittal resulted in a dis-
proportionate effort in resolving or meeting them. Additional
attention must be made to ensure the early submittal and resolution of
Shuttle experiment return requirements.

S.L.L. No.: 13-4

TITLE: USE OF MINI-COMPUTER FOR PROCESSING EARTH RESOURCES EXPERIMENT
DATA

LESSON LEARNED:

1. The use of minicomputer technology for processing Earth resources
    experiment package (EREP) data was basically cost effective and
    technically valid.

2. For a facility concept like the EREP, sensor designs and ground
    processing requirements for the experiment data should be developed
    in parallel. The user's (principal investigator's) requirements
    should be considered early in the software development phase. This
    approach should result in a more efficient, cost-effective, data-
    processing system.

3. Develop computer loading models early; update through implementation.

BACKGROUND: The Earth resources production data system was designed to
process electronic sensor data collected remotely in both spacecraft
and aircraft overflights. The system included two fully equipped mini-
computers, manufactured by the Digital Equipment Corporation, each of
which contained 48K of core memory, 32K of semiconductor memory, four
tape transports, two disks, a line printer, a card reader, teletype, a
display and keyboard, high-density tape, and an instrumentation recorder.
The system allowed for data conversion to tape, then plots, microfilm,
etc. Raw processing speed was comparable to large systems.

TITLE: SELF-BALANCING TECHNIQUE USED IN S194 L-BAND RADIOMETER

LESSON LEARNED: The self-balancing technique used in the S194 L-band radiometer provided an adaptive integration constant with a long-time constant during steady-state conditions and a much shortened effective time constant when a transient in brightness temperature was followed. This measurement technique worked effectively and should be considered for other types of sensors.

BACKGROUND: During design of the S194 radiometer, this technique was selected to ensure the best accuracy and sensitivity. Radiometers of this type are very susceptible to gaining variations of their amplifier circuits, and the self-balancing technique separated this effect from changes caused by the signal being measured.

SECTION 14

INTEGRATION

S.L.L. No.: 14-1

TITLE: INTERFACE VERIFICATION (FIT-CHECK) MATRIX REQUIREMENTS

LESSON LEARNED: Interface verification matrices should be established to ensure adequate fit checks of critical Government furnished equipment (GFE) hardware interfaces. A specific organization should be charged with the responsibility for generating and completing these matrices.

BACKGROUND: For the Skylab Program, fit-check matrices were developed and implemented for all interfaces between GFE to GFE and GFE to contractor furnished equipment (CFE). Development of the matrices was accomplished over a 6-month period. The matrices were generated for every baselined GFE hardware item, including all changes to the baseline designs as applicable. This system was found satisfactory for ensuring that all critical interfaces were verified before flight. Omission of the noncritical hardware might have saved some time and effort without penalty.

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